Materials Testing Machine

Design, Fabrication, and Assembly of a Benchtop Universal Materials Tester

A Major Qualifying Project Report:

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by:

Michael Cuddy (ME) 2022

Timothy Reno Baci Snow (ME) 2022

Kevin Neidhart (ME) 2022

Griffin O'Neil (ME) 2022

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Completed under the advisement and approval of:

Project Advisors

Professor Fiona Levey

Professor Robert Daniello

Worcester Polytechnic Institute

WPI

Abstract

The goal of this project was to prototype an inexpensive, easy-to-use, universal materials tester for hands-on learning in large undergraduate classroom settings. The project realized the design, fabrication, and assembly of a 26”x8”x7” benchtop machine able to apply tensile loads to round and flat specimens. The design is modular, with compression, wire, and bending test capabilities. Supplemental materials include a comprehensive operational package including CAD, CAM, and pertinent resources to implement the maintenance and development of current and future machines.

Acknowledgments

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I. Introduction

A universal materials tester is a device commonly used to precisely measure the response of a material to tensile, compressive or bending loads. It is used to generate stress-strain curves in order to document the material properties of a given specimen. Most industry-standard models come with a wide variety of features such as an integrated electronic user-interface panel, a control monitor with advanced programming and sensors, industry-grade extensometers, and more, thus making them expensive for teaching applications, and in some cases isolating the user from the physics of the testing process. The Mechanical and Materials Engineering Department of WPI would like to offer the ability to use and learn from a basic materials tester to undergraduate students enrolled in materials science-related courses and projects in order to produce stress-strain curves and assist in the study of materials. As the capabilities of commercially-available testers are generally much greater than what would be required for classroom and demonstration use, this team was tasked with developing and manufacturing a design and prototype for materials testers for use by the school. This machine had to be capable of testing specimens from elastomers to mild steel in tension, compression and bending while also fitting within the allocated $1,000 project budget (with the goal of producing another three to four machines with an additional $1,000).

II. Methodology

The upcoming section details initial research completed to understand the mechanics and components of universal materials testers as well as how the project was approached and collaborated on as a team.

i. Background and Research

Material properties along with their understanding and documentation are a critical aspect to the functioning of modern infrastructure and society; and because of this inherent significance, materials testers have become an important tool within engineering-based industries since their inception in the late 19th century.

Although materials testers have made great advancements in their capabilities, their overall mechanics have stayed similar since their initial designs in the late 19th century [9]. These machines have key components such as a load frame, upper and lower crossheads with grips, and at least one lead screw or driving mechanism. When materials testers first came to be, the testing force was applied to a specimen through the use of a gear train and hand crank and was measured using a weighing table along with scales and a poise. Modern-day testers, such as a commercially available Instron machine, typically utilize either hydraulics or a motor for force application and often have an automatic digital readout for forces to plot stress-strain curves.

Materials testers generally have a fixed and a driving crosshead, with the load cell fixed to the driving crosshead to measure the forces applied during the test. The rotational motion of the lead screw translates the crosshead to apply force to a specimen; the force is measured by a load cell then interpreted using a calibration factor via a microcontroller. Typically, materials testers have a vertical orientation where the crosshead translates vertically. When doing initial research, the team researched a vertically oriented testing machine, but determined to utilize a horizontal design after looking into various inexpensive horizontal testers for basic applications, one example of which, found on Instructables, is shown in **Figure 1** [3]. This machine is only capable of testing in tension, is mostly made of plastic, is powered by a motor, and utilizes an S-Type load cell. The team utilized a similar conceptual layout of fixed and driving crossheads and uniaxial linear motion rods along which the driving crosshead translates. The team planned to create a machine that was able to test a wider range of materials in both tension and compression as well as under bending.

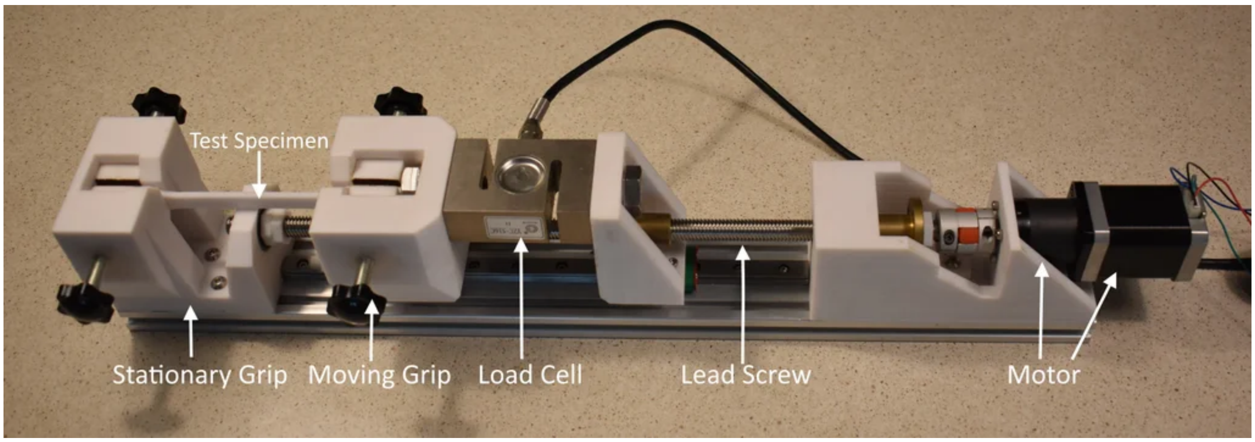


Figure 1: Example of a Horizontally Oriented Materials Tester

Note: design found under Creative Commons on Instructables [3].

All specimens for testing have standard sizes, ASTM and ISO providing the leading industry standards. These standards are generally proportional when changing the specimen sizes for both flat and round samples, focusing on the length to diameter ratio for round specimens and the width to thickness ratio for flat specimens. It was an objective of this project to test standard sample sizes.

ii. Project Approach

The primary constraint for this project was the cost of purchase, fabrication, and assembly materials and that played a large role in how the design process developed. It was determined that the best way to meet this cost constraint would be to minimize both the overall size and the complexity of the materials tester while still maintaining maximum functionality, efficiency, and overarching design objectives; a hand-operated materials tester with translating crossheads was thus chosen. Although this eliminated the possibility of testing high-strength metals and ceramics, the materials testing machine still maintained the ability to test materials with strength up to that of mild steel, while the simplicity significantly reduced cost. A materials chart, shown in **Table 1** and **Table 2**, was developed to determine the tensile strength of a wide range of materials to create a baseline minimum force that would need to be created by the machine. Research was conducted on types and functions of materials testers and ASTM standards were used to develop a standardized sizing of round and flat test specimens that would allow the testing of materials with strength up to that of mild steel. From there, force constraints were set and work was started on designing a benchtop tensile and compressive materials tester that would be able to provide the specified load to break the desired range of materials; all while being able to test in tension, compression, and bending.

III. Design

The following chapter will start with the overarching design constraints and requirements and then move on to the final design and its components' respective iterations and evolutions.

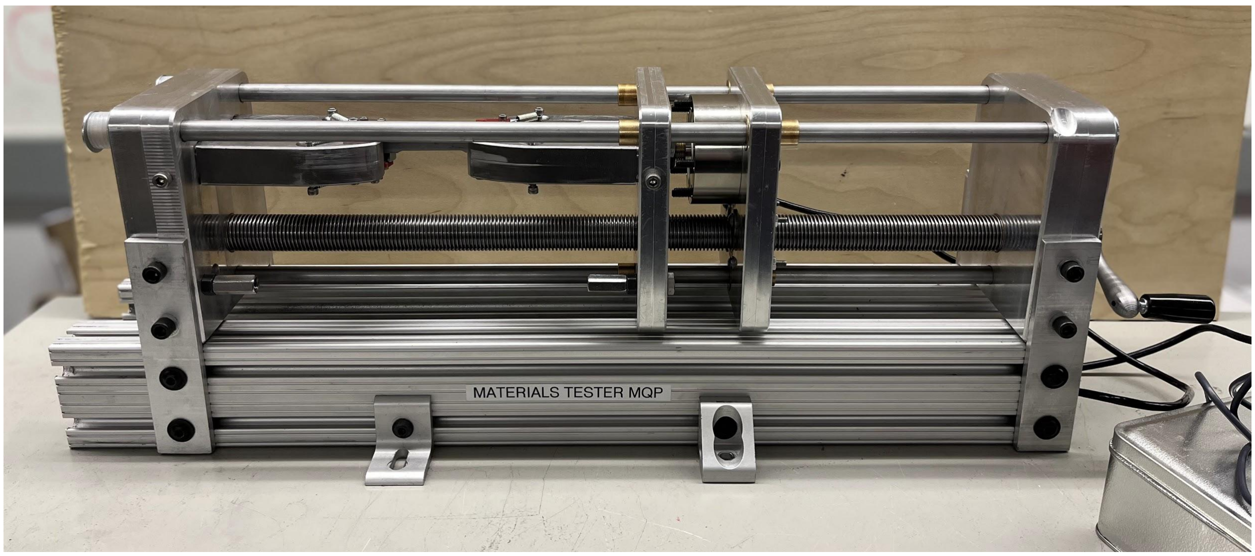


Figure 2: Physical Materials Tester Prototype

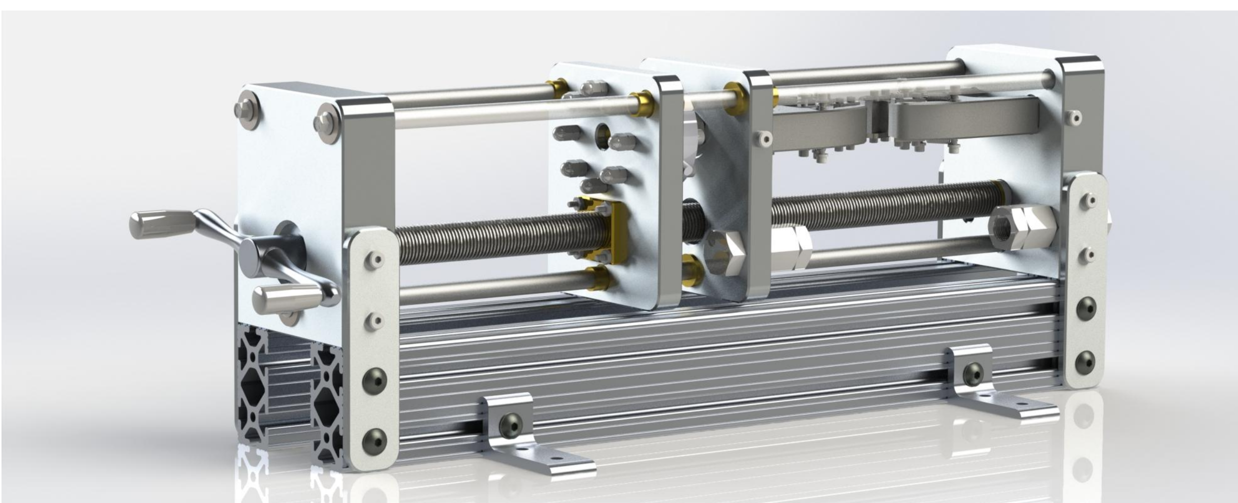


Figure 3: CAD Materials Tester Prototype

i. Design Constraints and Requirements

a. Budget

As mentioned during problem framing, the main financial constraint and objective that the team wished to meet was to create a machine that is at a much lower net cost than that of an advanced, industry-grade tester. The standard budget for an MQP at WPI is $250.00 per student, making a total initial budget of $1000.00. The Mechanical and Materials Engineering Department was willing to provide an additional $1000.00 after a feasible prototype has been created and realized in order to create a small production run of testing machines. The goal was to be able to produce a total of four to five machines, with each machine for around $400.00. rought the budget per machine to around $400.00.

b. Size Constraints

As far as size and overall dimension constraints for the project, the materials tester required a large enough lateral distance to allow for maximum material planned elongation and large enough frames and crossheads to allow for robust movement and rigidity. Based on sample sizing and planned elongation of the testing specimens, a minimum travel distance required is 6” for the standard sheet-sized flat samples and 3” for the subsize standard flat samples. As the necessary components of the machine were incorporated, the overall running length of the machine increased while keeping this baseline requirement in mind in order to accommodate maximum material elongation based on selected samples and their sizes. In addition, it needed to be small enough to both fit on a benchtop and be able to be transported by cart.

c. Materials Selection

In order to begin designing a tester, it was necessary to select which materials the machine could test. The 'upper limit' of the project was set at mild steel. This was because stronger steels and ferrous metals require relatively larger forces to break, increasing cost without any significant change in educational value. The 'lower limit' was set by polymers with a very high percent elongation. This was because polymers with a high ductility can stretch to five times their length or longer, thus requiring the machine to have a larger testing area. To select a library of materials, the team filtered standard materials from a standard introductory materials science textbook [2]. The team filtered these materials based on materials with tensile strength less than 300-400 MPa and materials having a percent elongation of less than 200% to meet the aforementioned criteria. This filtering was done initially with no regard to material cost and then commercially available rods and sheets of each respective 'fit' material were sourced. From this process, the team was able to select, out of select commonly available materials: two plain carbon and low alloy-steels, one stainless steel alloy, three cast irons, five aluminum alloys, five copper alloys, two magnesium alloys, one titanium alloy, eleven elastomer polymers, two 3D printed materials, and a minimum of three grades of wood. The data of the material library can be found in **Table 1** and **Table 2** below.

The following library details the selected general materials for the materials tester machine based on criteria of having:

a). Tensile strength less than 400 MPa

b). Maximum percent less than 200%

Note: This materials library can also be found in the project's comprehensive operational package.

									Cross Sectional Area (m^2)				
	Material Library								E8 Fig. 8-1	E8 Fig. 8-2	E8 Fig. 8-3	E8 Fig. 8-4	E8 Fig. 8-5
	indicates an average								1.23E-04	6.36E-05	2.83E-05	1.26E-05	4.91E-06
	Material	ROD	SHEET	density (g/cm^3)	density (kg/m^3)	fracture toughness	notes	compr. strength (MPa)	yield strength (MPa)	**tensile strength (MPa)**	notes	modulus of elasticity (GPa)	percent elongation (%)
Plain Carbon & Low-Alloy Steels	Low-Carbon Steel 1018	Rod	Sheet	7.87	7870		Cold Worked, B85		344.7	440.0		205.0	15.0
Plain Carbon & Low-Alloy Steels	Steel Alloy 1020	Rod	Sheet	7.85	7850				210.0	380.0	(hot rolled)		25.0
Stainless Steels	Stainless Alloy 405	Rod	Sheet	7.80	7800				170.0	415.0	815°C (annealed)	200.0	20.0
Cast Irons	Grade G1800	Rod	Sheet	7.30	7300				-	124.0		81.5	-
Cast Irons	Grade G3000	Rod	Sheet	7.30	7300				-	207.0		101.5	-
Cast Irons	Grade G4000	Rod	Sheet	7.30	7300				-	276.0		124.0	-
Aluminium Alloys	Alloy 1100	Rod	Sheet	2.71	2710				34.0	90.0		69.0	40.0
Aluminium Alloys	Alloy 2024	Rod	Sheet	2.77	2770	44.0	T3		75.0	185.0		72.4	20.0
Aluminium Alloys	Alloy 6061	Rod	Sheet	2.70	2700				55.0	124.0		69.0	30.0
Aluminium Alloys	Alloy 7075	Rod	Sheet	2.80	2800	24.0	T651		103.0	228.0		71.0	17.0
Aluminium Alloys	Alloy 356.0	Rod	Sheet	2.69	2690				124.0	164.0		72.4	6.0
Copper Alloys	C11000	Rod	Sheet	8.89	8890				69.0	220.0	electric tough pitch	115.0	45.0
Copper Alloys	C26000			8.53	8530				*112.5*	*332.5*	cartridge Brass	*110.0*	*61.0*
Copper Alloys	C36000			8.50	8500				125.0	340.0	free-cutting brass	97.0	53.0
Copper Alloys	C71500			8.94	8940				140.0	380.0	Cu-Ni, 30%	150.0	45.0
Copper Alloys	C93200	Rod	Sheet	8.93	8930				125.0	240.0	bearing bronze	100.0	20.0
Magnesium Alloys	Alloy AZ31B	Rod	Sheet	1.77	1770	28.0			220.0	290.0		45.0	15.0
Magnesium Alloys	Alloy AZ91D	Rod	Sheet	1.81	1810				200.0	262.0		45.0	15.0
Titanium Alloys	Comm. pure (ASTM g1)	Rod	Sheet	4.51	4510				170.0	240.0		103.0	24.0
Elastomers	Epoxy	Rod	Sheet	*1.26*	1255	0.6	equiaxed grains		-	*58.8*	hot-fin and annealed	*2.4*	*4.5*
Elastomers	Nylon 6.6	Rod	Sheet	1.14	1140	*2.8*			*69.0*	94.5	as cast	*2.7*	*47.5*
Elastomers	Phenolic	Rod	Sheet	1.28	1280				-	*48.3*	annealed, O temper	*3.8*	*1.8*
Elastomers	PBT			1.34	1340				*58.3*	*58.3*	oil quench, tempered	*2.5*	*175.0*
Elastomers	PC			1.20	1200	2.2			62.1	*67.6*	solution heat-treat	*2.4*	*130.0*
Elastomers	Polyester (Thermoset)	Rod	Sheet	*1.25*	1250	0.6			-	*65.6*	sand cast	3.2	2.6
Elastomers	PEEK			1.31	1310				91.0	*86.7*	rolled	*1.1*	*90.0*
Elastomers	PET			1.35	1350	5.0			59.3	*60.4*		*2.4*	*165.0*
Elastomers	PMMA	Rod	Sheet	1.19	1190	*1.2*			*63.5*	*60.4*		*2.9*	*3.8*
Elastomers	PS	Rod	Sheet	1.05	1050	*0.9*			*47.0*	*43.8*		*3.3*	*1.9*
Elastomers	PVC	Rod	Sheet	*1.44*	1440	*3.0*			*42.8*	*46.2*		*3.3*	*60.0*
3D Printed Material	ABS	Print	Print	1.04	1040					40.0		*4.6*	*26.8*
3D Printed Material	PLA	Print	Print	1.24	1240					37.0		4.0	6.0
Wood	Douglas fir (12% mois)			0.48	480			*47.2*	*86.0*	*108 / 2.4*		13 / 0.61	-
Wood	Pine wood							*41.2*	*79.5*	*40.0*		9.0	-
Wood	Oak wood							*51.4*	*99.5*	-		11 / 0.625	-

Table 1: Material Library - Properties Based

	Calculations											
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 5l	Specimen 4l	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
	Force Required to Break (kN)	Force Required to Break (kN)	Force Required to Break (kN)	Force Required to Break (kN)	Force Required to Break (kN)	Force Required to Break (kN)	Force Required to Break (kN)	Add. Length Required to Break (cm)	Add. Length Required to Break (cm)	Add. Length Required to Break (cm)	Add. Length Required to Break (cm)	Add. Length Required to Break (cm)
	12.5mm	**9.0mm**	**6.0mm**	**4.0mm**	**2.5mm**	**.113in**	**.160in**					
Low-Carbon Steel 1018	53.996	27.992	12.441	5.529	2.160	2.822	5.708	0.75	0.54	0.36	0.24	0.15
Steel Alloy 1020	**46.633**	**24.175**	**10.744**	**4.775**	**1.865**	**2.437**	4.929	**1.25**	**0.90**	**0.60**	**0.40**	**0.25**
Stainless Alloy 405	**50.928**	**26.401**	**11.734**	**5.215**	**2.037**	**2.661**	5.383	**1.00**	**0.72**	**0.48**	**0.32**	**0.20**
Grade G1800	15.217	7.889	3.506	1.558	0.609	0.795	1.608	-	-	-	-	-
Grade G3000	25.403	13.169	5.853	2.601	1.016	1.327	2.685	-	-	-	-	-
Grade G4000	33.870	17.558	7.804	3.468	1.355	1.770	3.580	-	-	-	-	-
Alloy 1100	11.045	5.726	2.545	1.131	0.442	0.577	1.167	2.00	1.44	0.96	0.64	0.40
Alloy 2024	22.703	11.769	5.231	2.325	0.908	1.186	2.400	1.00	0.72	0.48	0.32	0.20
Alloy 6061	15.217	7.889	3.506	1.558	0.609	0.795	1.608	1.50	1.08	0.72	0.48	0.30
Alloy 7075	27.980	14.505	6.447	2.865	1.119	1.462	2.958	0.85	0.61	0.41	0.27	0.17
Alloy 356.0	20.126	10.433	4.637	2.061	0.805	1.052	2.127	0.30	0.22	0.14	0.10	0.06
C11000	26.998	13.996	6.220	2.765	1.080	1.411	2.854	2.25	1.62	1.08	0.72	0.45
C26000	40.804	21.153	9.401	4.178	1.632	2.132	4.313	3.05	2.20	1.46	0.98	0.61
C36000	41.724	21.630	9.613	4.273	1.669	2.180	4.410	2.65	1.91	1.27	0.85	0.53
C71500	46.633	24.175	10.744	4.775	1.865	2.437	4.929	2.25	1.62	1.08	0.72	0.45
C93200	29.452	15.268	6.786	3.016	1.178	1.539	3.113	1.00	0.72	0.48	0.32	0.20
Alloy AZ31B	35.588	18.449	8.200	3.644	1.424	1.860	3.762	0.75	0.54	0.36	0.24	0.15
Alloy AZ91D	32.152	16.668	7.408	3.292	1.286	1.680	3.399	0.75	0.54	0.36	0.24	0.15
Comm. pure (ASTM g1)	29.452	15.268	6.786	3.016	1.178	1.539	3.113	1.20	0.86	0.58	0.38	0.24
Epoxy	7.216	3.741	1.663	0.739	0.289	0.377	0.763	0.23	0.16	0.11	0.07	0.05
Nylon 6.6	11.597	6.012	2.672	1.188	0.464	0.606	1.226	2.38	1.71	1.14	0.76	0.48
Phenolic	5.927	3.073	1.366	0.607	0.237	0.310	0.627	0.09	0.06	0.04	0.03	0.02
PBT	7.154	3.709	1.648	0.733	0.286	0.374	0.756	8.75	6.30	4.20	2.80	1.75
PC	**8.296**	**4.301**	**1.911**	**0.849**	**0.332**	**0.434**	0.877	**6.50**	**4.68**	**3.12**	**2.08**	**1.30**
Polyester (Thermoset)	8.044	4.170	1.853	0.824	0.322	0.420	0.850	0.13	0.09	0.06	0.04	0.03
PEEK	10.634	5.512	2.450	1.089	0.425	0.556	1.124	4.50	3.24	2.16	1.44	0.90
PET	7.406	3.839	1.706	0.758	0.296	0.387	0.783	8.25	5.94	3.96	2.64	1.65
PMMA	7.406	3.839	1.706	0.758	0.296	0.387	0.783	0.19	0.14	0.09	0.06	0.04
PS	5.375	2.786	1.238	0.550	0.215	0.281	0.568	0.09	0.07	0.04	0.03	0.02
PVC	5.670	2.939	1.306	0.581	0.227	0.296	0.599	3.00	2.16	1.44	0.96	0.60
ABS	4.909	2.545	1.131	0.503	0.196	0.257	0.519	1.34	0.96	0.64	0.43	0.27
PLA	4.541	2.354	1.046	0.465	0.182	0.237	0.480	0.30	0.22	0.14	0.10	0.06
Douglas fir (12% mois)	-	-	-	-	-	-	-	-	-	-	-	-
Pine wood	4.909	2.545	1.131	0.503	0.196	0.257	0.519	-	-	-	-	-
Oak wood	-	-	-	-	-	-	-	-	-	-	-	-

Table 2: Material Library - Calculation Based

d. Test Specimen Selection

Test specimens were based on the standards established for tensile and compression testing (ASTM E8/E8M - 16a and ASTM 9 - 09, respectively). For compressive specimens, the standards specified the usage of two flat bearing blocks for sample mounting or the usage of one bearing block and a spherical seated bearing block to allow for additional rigidity during compression (see **Figures 4**, **5**, and **Table 3**). The ASTM E9 - 09 standard also recommends setups for compressive testing jigs, apparatus, and sample sizes including thin sheets and cylinders.

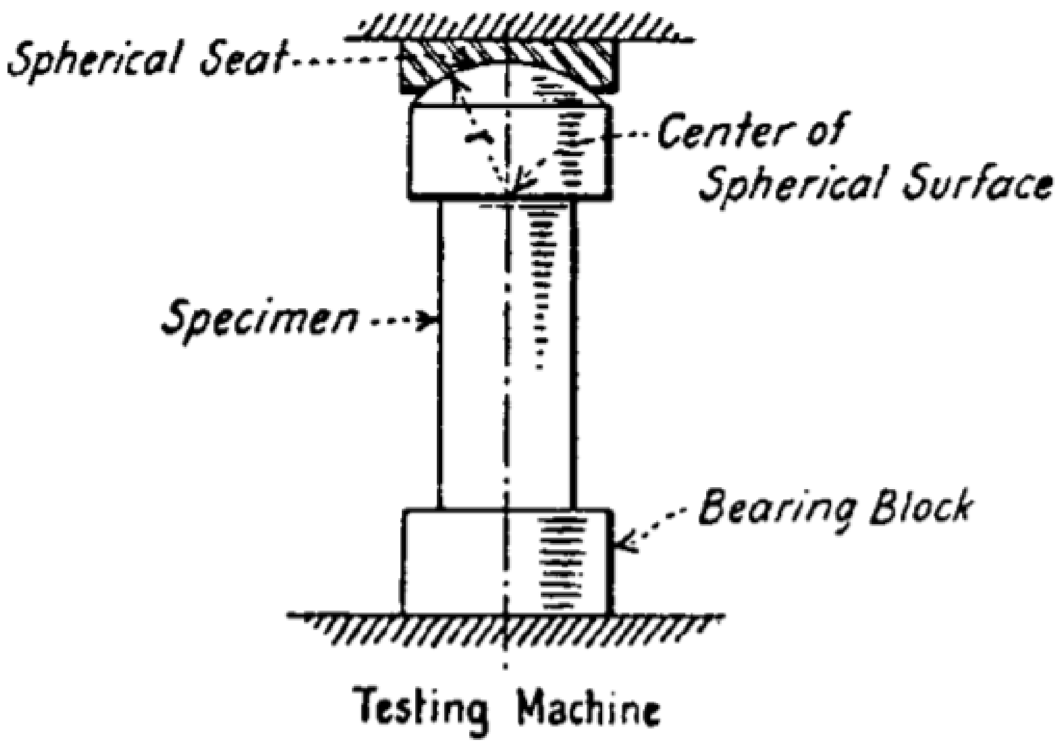


Figure 4: Compressive Bearing Block Illustration I

Note: spherical seated bearing block illustration [4].

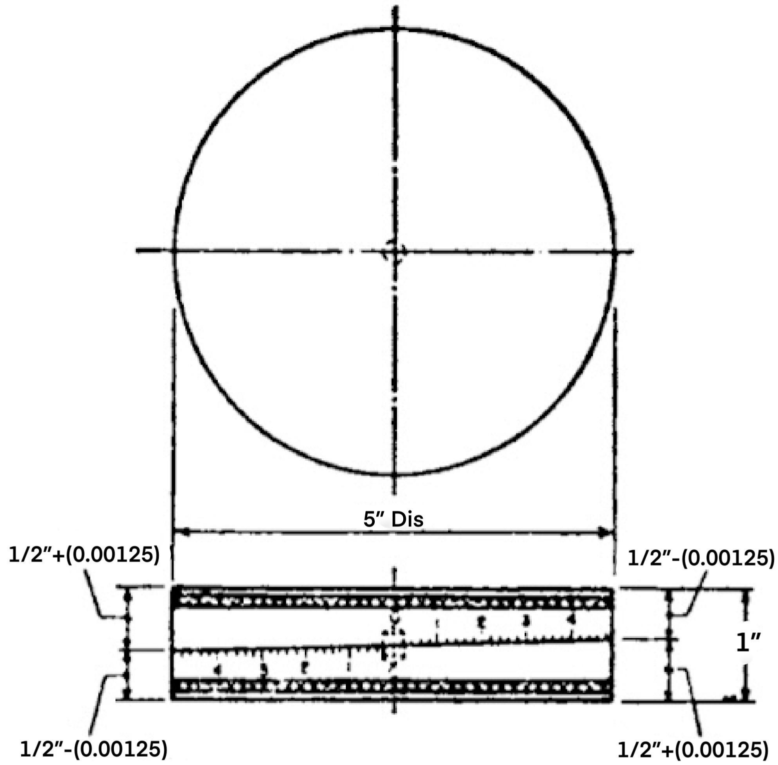


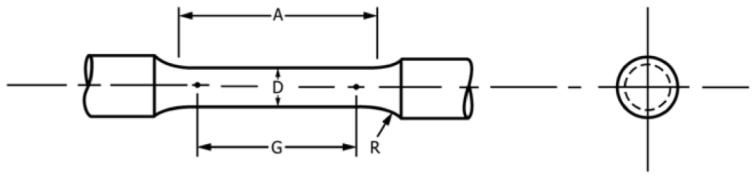
Figure 5: Compressive Bearing Block Illustration II

Note: bearing block detail [4].

The ASTM E8/E8M - 16a standard for the tensile testing of metallic materials is a detailed and intricate documentation and includes various types of adaptive round, flat, and wire test specimens, a wide range of adaptive grips, and the interpretation of test data. For this project's scope, the machine was constrained to be able to test both round and flat samples, with the room to test wire specimens. For round samples, the team selected the specimens 3, 4, and 5 (**Table 3** below) as small-size specimens proportional to the standard specimen [5].

These were smaller cross-sectional round samples and allowed for the toughest tensile material to break with a required maximum force of around 2.16kN, determined via maximum required force for strongest material in the materials library, something that is very achievable with a small-budget design.

E8/E8M – 16a



Dimensions, mm [in.] For Test Specimens with Gauge Length Four times the Diameter [E8]					
	Standard Specimen	Small-Size Specimens Proportional to Standard			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G—Gauge length	50.0 ± 0.1 [2.000 ± 0.005]	36.0 ± 0.1 [1.400 ± 0.005]	24.0 ± 0.1 [1.000 ± 0.005]	16.0 ± 0.1 [0.640 ± 0.005]	10.0 ±0.1 [0.450 ± 0.005]
D—Diameter (Note 1)	12.5 ± 0.2 [0.500 ± 0.010]	9.0 ±0.1 [0.350 ± 0.007]	6.0 ± 0.1 [0.250 ± 0.005]	4.0 ± 0.1 [0.160 ± 0.003]	2.5 ± 0.1 [0.113 ± 0.002]
R—Radius of fillet, min	10 [0.375]	8 [0.25]	6 [0.188]	4 [0.156]	2 [0.094]
A—Length of reduced parallel section, min (Note 2)	56 [2.25]	45 [1.75]	30 [1.25]	20 [0.75]	16 [0.625]

Table 3: ASTM Standard Round Specimen Dimensions

Note: figure provided by ASTM International, E8/EM - 16A [5].

For flat samples as standardized by ASTM E8, the thickness and width of each ‘dogbone-shaped’ sample are variable, allowing for the samples themselves to range within a variety of materials and cross-sectional areas.

e. Modularity

The key design concept behind this materials tester was modularity. This allowed the project to adapt and evolve with ease as design decisions were made, changed, or removed - and also allowed for further future adaptations and changes. The modularity of the design was best illustrated in an early systems drawing, highlighting the adaptability of test fixtures and grips, load cells, fixturing of the driving crosshead to the lead screw, and the driving of the lead screw itself. This systems drawing can be seen in **Figure 6** below:

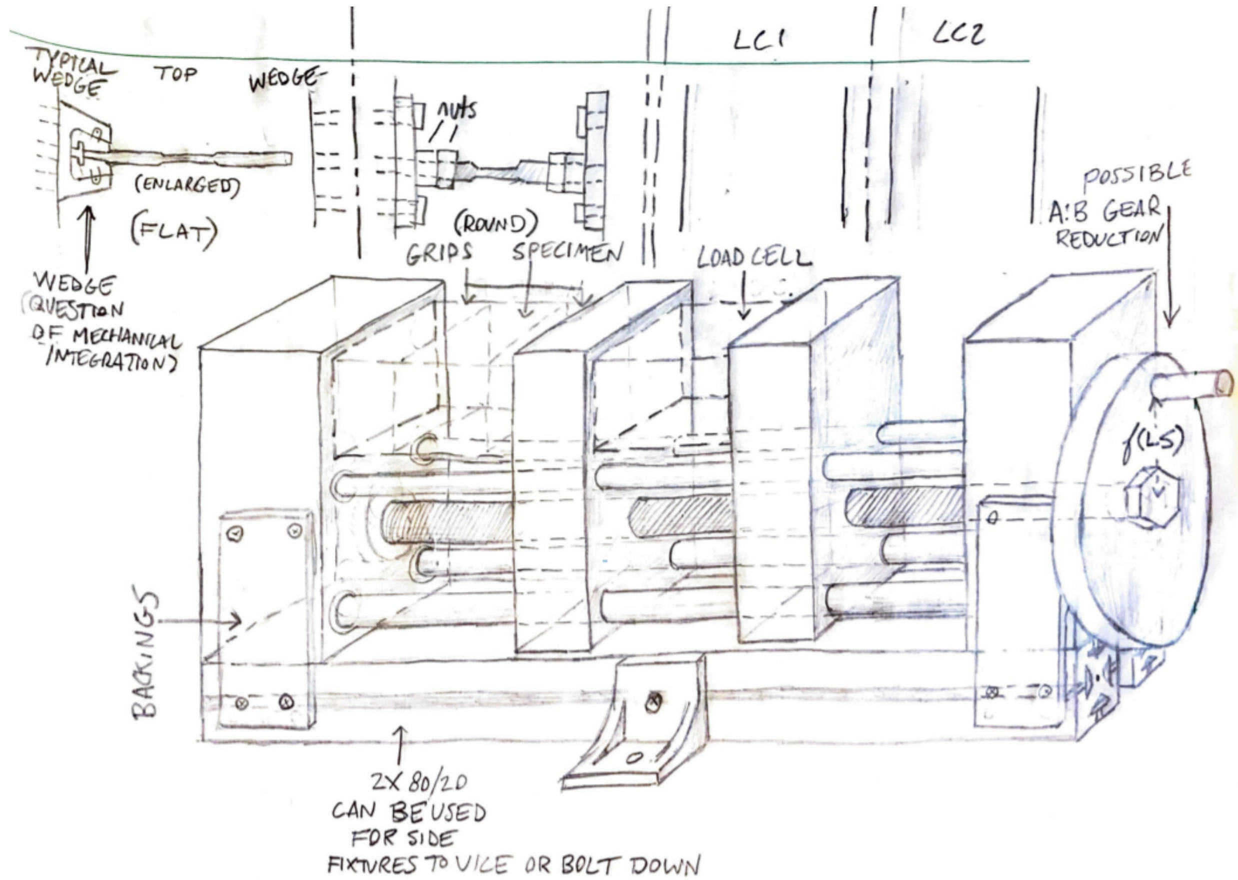


Figure 6: Refined Systems Drawing

For the most part, the compressive capabilities of this project's machine were designed to be a function of its tensile capabilities. This initial focus on tensile testing was based on the fact that tensile properties and the tensile testing of materials being much more well documented than compressive properties. Additionally, tensile testing generally requires lower forces than compression testing. Allowances were also made for wire testing and three-point bending. Ultimately, based on the modularity of the tensile capabilities of the machine, the integration of other means of mounting and testing can follow in future design iterations.

f. Usage

This project was intended to provide WPI's Mechanical and Materials Engineering Department with materials testing machines that are compact and cheap enough that multiple working models could be used in a hands-on undergraduate lab or classroom. A group of students must be able to produce a fairly accurate and representative stress-strain curve if given a test specimen and one of these machines. It was determined that the machine should not require more manual input via a crank to operate than an average person could easily provide. The output data should equally be easy to compile, view, export, and interpret. Additionally, the machine should be able to be easily operated and serviced with simple, standard hand tools.

ii. Design Iterations

The final design of the materials tester was the product of many design iterations over the course of the academic year. This first started with determining the machine orientation, then in what manner to configure the machine's components, such as the layout of the crossheads and their respective features, adapting the design to incorporate more testing grips, then changing overall sizing to make it as compact and simple as possible. The following section outlines these developments and other challenges that were faced with respective components of the machine and the steps that were taken to overcome those challenges from initial brainstorming to prototyping to produce effective results.

a. Body

Initial designs from the team took shape similar to that of a 3D printer. Initial sketches and drawings are shown in the **Figures** below:

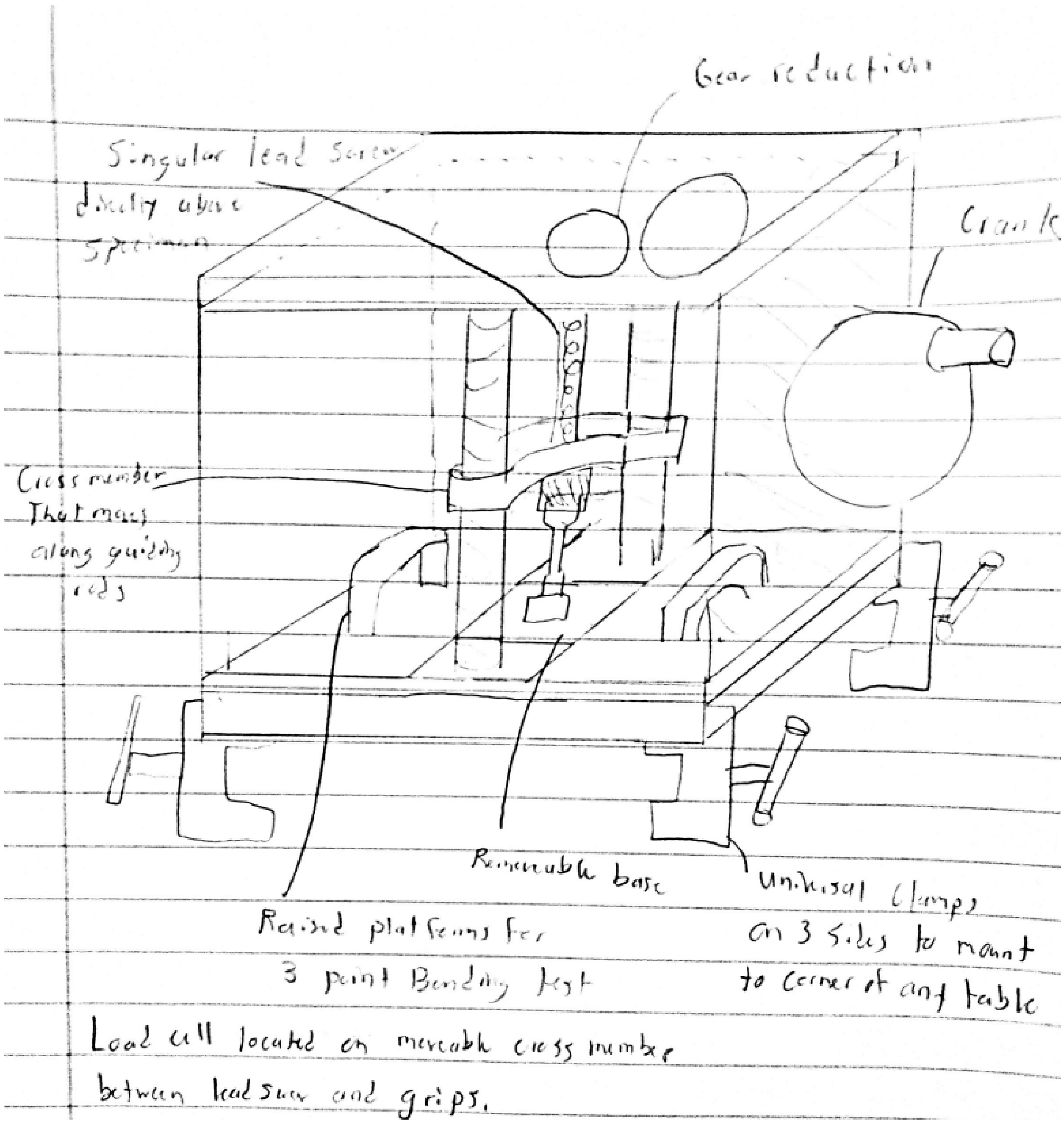


Figure 7: Early Concept Drawing I

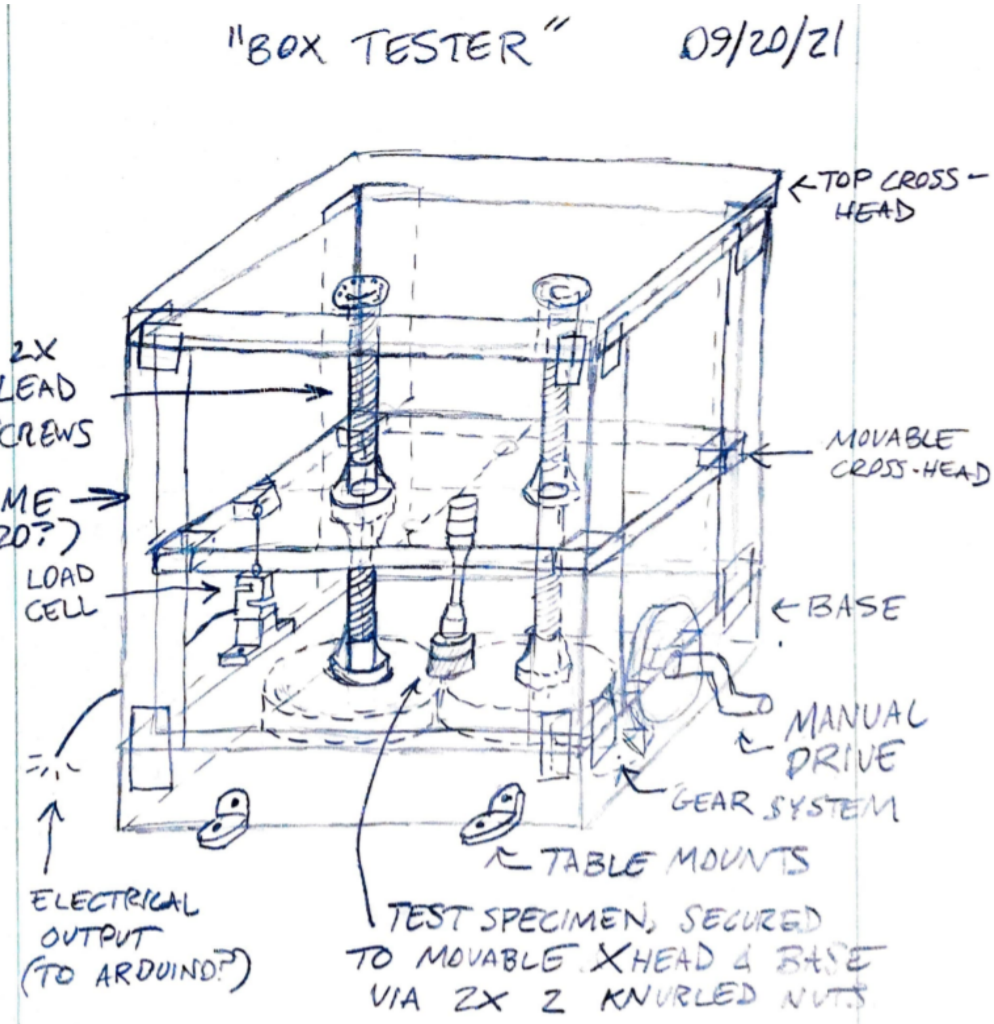


Figure 8: Early Concept Drawing II

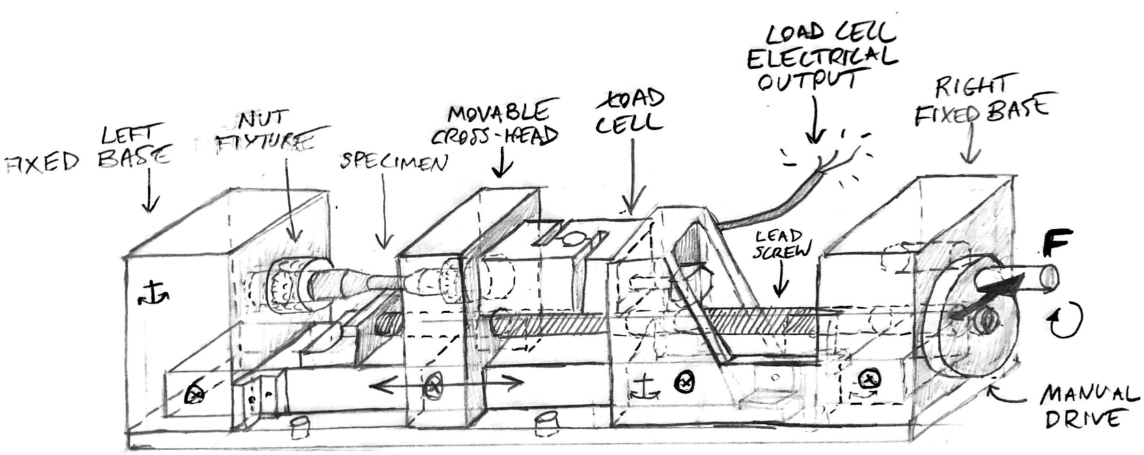


Figure 9: Early Concept Drawing III

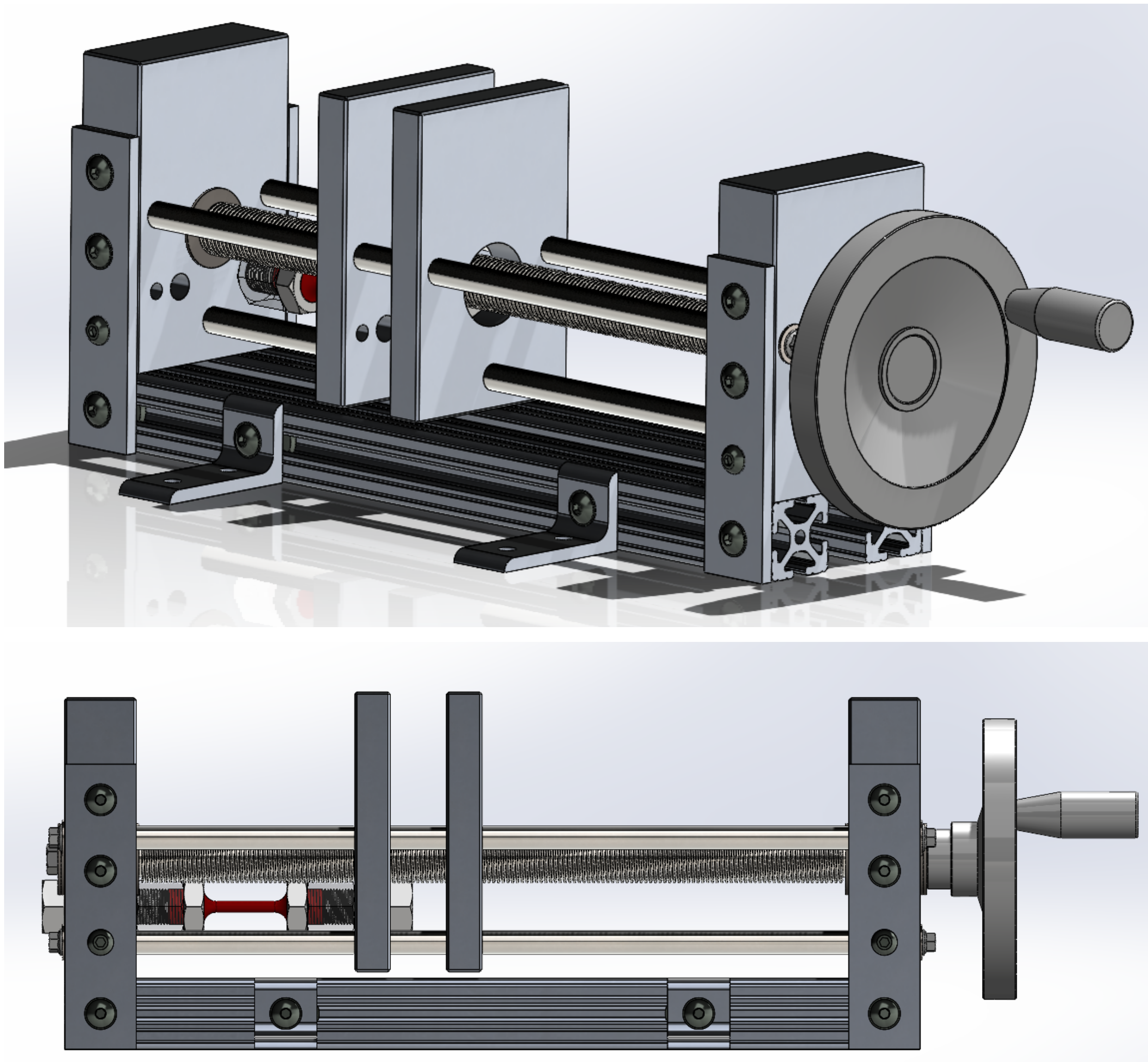


Figure 10: Early CAD Assembly

After further research was conducted, It was decided a horizontally oriented materials tester might be both easier to manufacture and result in a more compact design. This design layout would save on total material costs, and be easier to secure to a surface. The initial horizontal tester design shown in **Figure 10** above implemented 4”x6.5” crossheads, and had the linear motion rods running level with the lead screw. When further analyzing this design iteration, it was found that the crossheads would have been costly to purchase at this height, and over ⅓ of the material load would go to waste. It was also found the linear motion rods would not be able to properly support the loads from the upper grips. From there, the crosshead sizes were adjusted to 5”x6”, and the linear motion rods were moved to the top of the crossheads as shown in **Figure 11** below. This design features segments of 3”x1.5” extruded 80/20 for the base and 6061 aluminum middle and end crossheads. The supporting rods are made from turned, ground, and polished steel rods and the body also has side L-brackets attached to the 80/20 that will allow it to be mounted to any table. Work was also completed on the design of mounting feet to be mounted to the left end crosshead such that the machine can be mounted and operated vertically. These solid parts can be found in the operational package’s CAD folder.

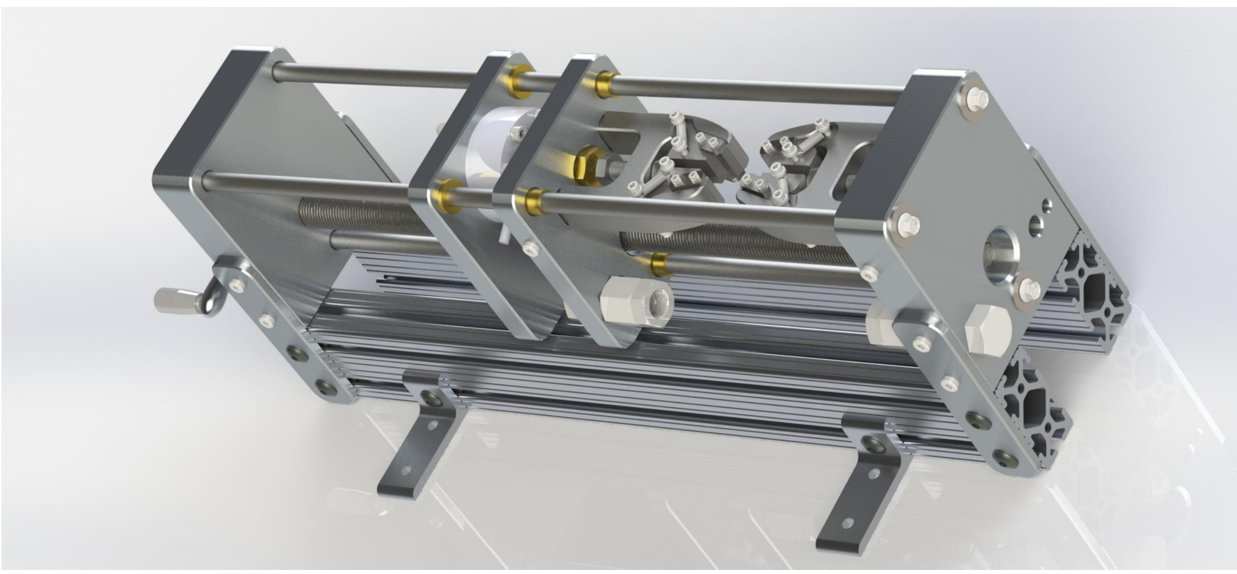


Figure 11: CAD Model of Universal Materials Tester Prototype Design

b. Load Cell

When researching material properties in tension, it was determined that the maximum load force to be handled out of the selected materials (1018 low-carbon steel with 2.5mm diameter) would be roughly 2.160kN or 486 lbf. When taking this into consideration, 500-1000lbf load cells were targeted such that there would be more than enough range for force readings, given variations and inaccuracies in load cell resolutions. The main consideration when researching these load cells was deciding between using S-Type or low-profile style load cells. The S-Type style is generally less expensive than low-profile, but is also more susceptible to moment forces, due to its S-Type body transmitting the load. The low-profile style load cell is often thin (around 1") and saves lateral space, while it also allows for purely axial force readings and is less susceptible to moment forces.

The team was able to select a low-profile load cell from AliExpress (DYLF-102) at an affordable price of $50.99. It is rated for 500 kgf or 1,102.31 lbf, meeting the project's resolution expectations. This load cell operates through a load button that generates a force applied to the system, thus producing an electrical output for interpretation to generate data.

Below is **Figure 12** showing the load cell and **Table 4** listing its electrical specifications, respectively:

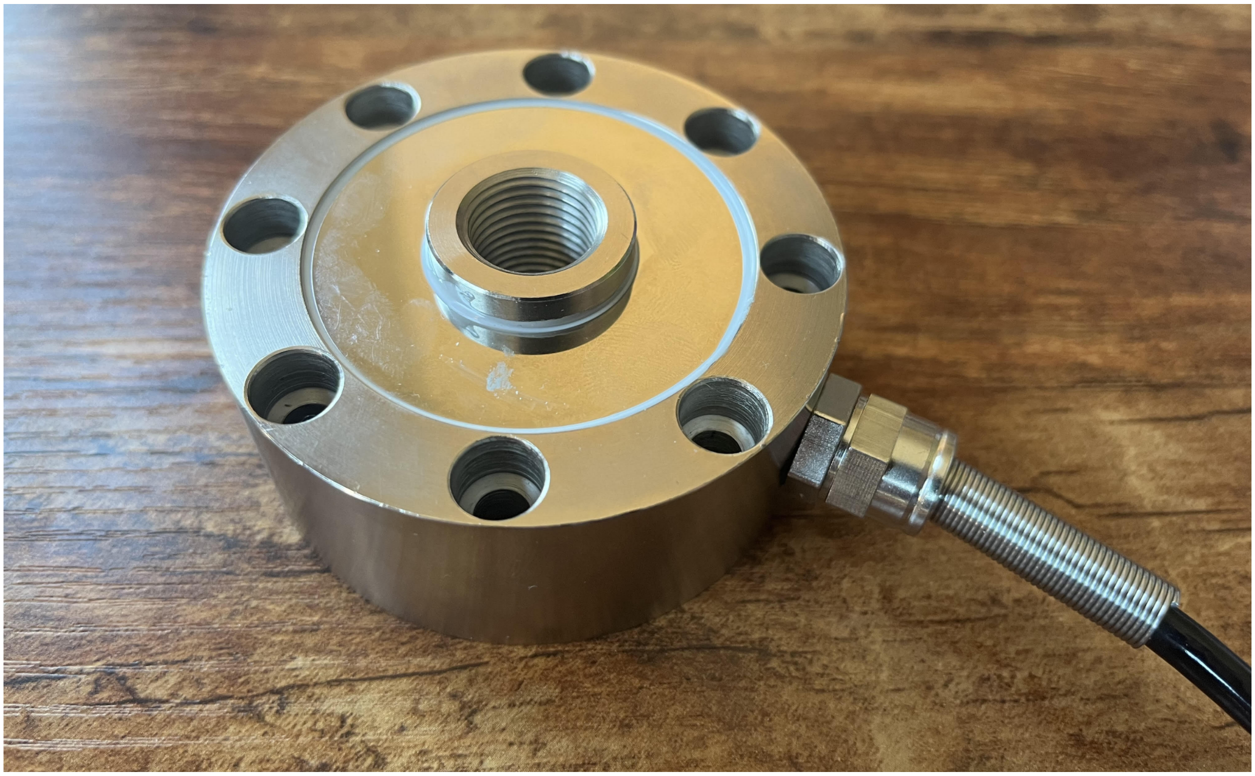


Figure 12: DYLF-102 Load Cell

Parameters	Unit	Technical Indicators	Parameters	Unit	Uncertainty
Sensitivity	mv/v	2.0±0.05	Sensitivity Temperature Coefficient	≤%f S/10°C	±0.03
Nonlinear	≤%f S	±0.03	Operating Temperature Range	°C	-20°C~ +80°C
Lag	≤%f S	±0.03	Input Resistor	Ω	750±20ω
Repeatability of	≤%f S	±0.03	Output Resistor	Ω	700±5ω
Creep	≤%f S/30min	±0.03	Security Overload	≤%f S	150% F. S
0-Point Output	≤%f S	±1	Insulation Resistance	MΩ	≥5000mω (50VDC)
0-Point Temp Coeff.	≤%f S/10°C	±0.03	Recommended Excitation Voltage	V	5v-15v

Table 4: DYLF-102 Load Cell Factory Electrical Specifications

To interpret the load cell, it was necessary to purchase an HX711 load cell amplifier to assist in reducing noise, while also providing a rigid and common programming framework. The resources available on manufacturer Sparkfun's website [10]. This includes an HX711 code package, calibration code, and operational code all of which can be found in **Appendix D**. The calibration and operational code can be found below; a comprehensive code package can also be found attached to the project's operational package as detailed further in **Chapter IV**.

c. Lead Screw

The linear motion was provided by an Acme threaded lead screw. It needed to be large enough to withstand the forces that would be put on it, and it needed to have high threads per inch to generate the required force. A 1" diameter satisfies the strength requirement and 10 threads per inch is the finest standard thread count for that size. Thread fit class 2G was chosen over class 2C because it was cheaper, and the extra precision of 2C is not needed. A 6' carbon steel lead screw was chosen which would allow for the creation of three machines once cut to length. The screw has a tensile strength of 53,000 psi which is well above the strength required for the materials tester. Sheathing options for the lead screw were explored to prevent dust and debris from specimens from becoming lodged in the threads. The compression requirements of such a sheathing were difficult to meet. Options for a sliding or collapsible sheath were also discussed but were ultimately also dismissed.

To secure the crosshead to the lead screw a flange nut was needed, but the steel ones available for purchase were too expensive for the standard budget requirements and WPI did not have the tool required for the team to make 1"-10 Acme threads ourselves. Instead, the team used a much cheaper brass square nut. The nut was milled so that most of its length had the corners removed, leaving it as a circular nut with a square flange. Thus the team was able to manufacture an inexpensive flange nut without needing threading tools.

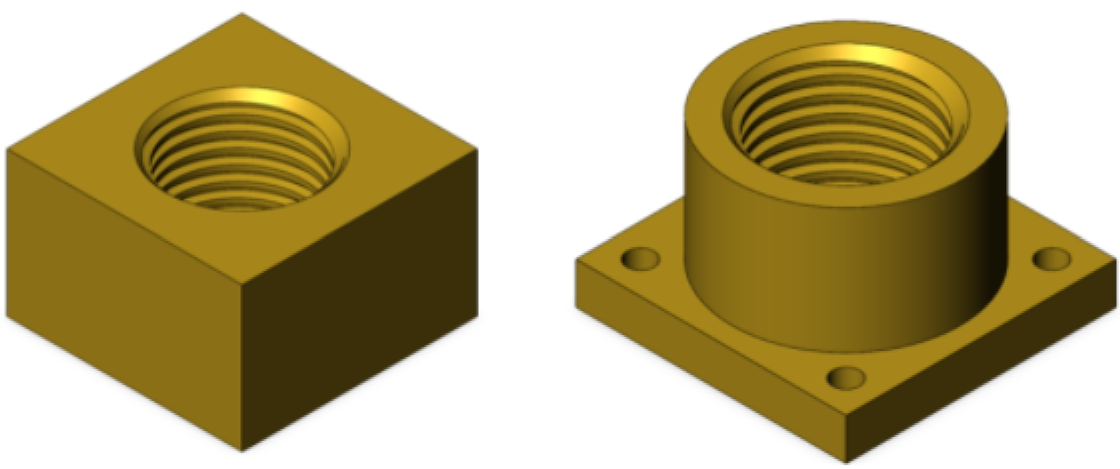


Figure 13: Brass Nut as Purchased (Left) and After Machining (Right) CAD

d. Round Sample Grips and Testing

To complete a tensile test, it was necessary to prepare fixturing structures for both flat and round types of specimens. For round specimens, all fixturing designs were made with strict adherence to ASTM guidelines, which essentially called for minimum and maximum sizes for dimensions of respective samples to allow for secure, uniaxial testing. These sizes which were created to fit Imperial threading and length-based features can be found in **Table 5** below. This modularity of design is exhibited in the below **Figure 14** from ASTM's tensile testing standards. The library details the selected ASTM E8/E8M - 16a specimen types for round specimens including selected values for any minimum constraint in order to either create a). imperial sizes and threading or b). standard sizes between the specimens. These selected values to adhere to ASTM guidelines while also creating a round-numbered, standardized group of samples for the team's application are shown in the table as 'SELECTED.'

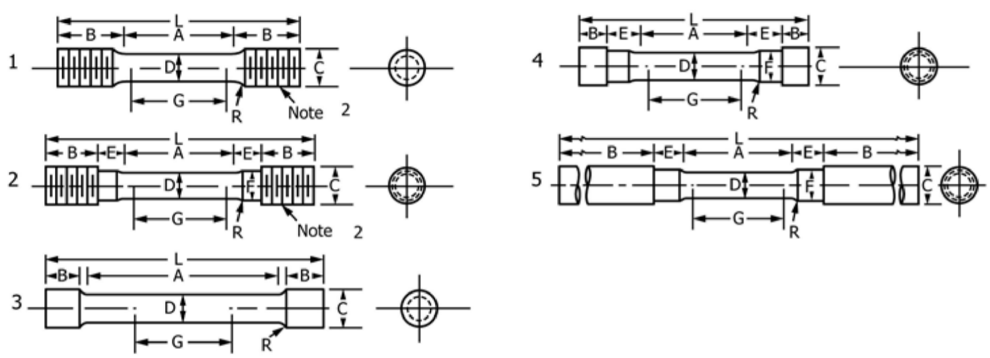


Figure 14: Free-Form Round Sample Processing

Type of Specimens >	*E8 Figure 8*	*Notes*	*E8 Figure 8*	*Notes*	*E8 Figure 8*	*Notes*
12.5mm Round Tension Test Specimen and Examples of Small-Size Specimens Proportional to the Standard Specimen						
Specimen Number	Specimen 3	(+/-)	Specimen 4	(+/-)	Specimen 5	(+/-)
G - Gauge Length (mm)	24.000	0.100	16.000	0.100	10.000	0.100
R - Fillet Radius, min (mm)	6.000	-	4.000	-	2.000	-
A - Length of Reduced // Section, min (mm)	30.000	-	20.000	-	16.000	-
D - Diameter (mm)	6.000	0.100	4.000	0.100	2.500	0.100
Cross Sectional Area (mm^2)	28.274	0.010	12.566	0.010	4.909	0.010
Cross Sectional Area (m^2)	2.83E-05	1.00E-08	1.26E-05	1.00E-08	4.91E-06	1.00E-08
Cross Sectional Area (in^2)	4.38E-02	1.55E-05	1.95E-02	1.55E-05	7.61E-03	1.55E-05
R RADIUS, calculated (mm)	6.495	-	4.330	-	2.706	-
R RADIUS, calculated (in)	0.256	-	0.170	-	0.107	-
A SELECTED (mm)	30.000	-	20.000	-	16.000	-
A SELECTED (in)	1.181	-	0.787	-	0.630	-
A+2R, calculated (mm)	42.990	-	28.660	-	21.413	-
A+2R, calculated (in)	1.693	-	1.128	-	0.843	-
C End Diameter SELECTED (in)	0.750	3/4	0.500	1/2	0.313	5/16
L Total Length of Specimen, calculated (in)	3.193	-	2.628	-	2.343	-
B Length of End Section SELECTED (in)	0.750	standard	0.750	standard	0.750	standard
Threading (in)		**3/4-16**		**1/2-20**		**5/16-18**

Table 5: Selected Round Tension Test Specimen Dimensions

The round samples are mounted to the crossheads through clearance holes for the three different screw sizes chosen above; 3/4-16, 1/2-20, and 5/16-18. These three holes and their location can be seen on the left end crosshead in **Figure 15** below (3/4" to 5/16" left to right).

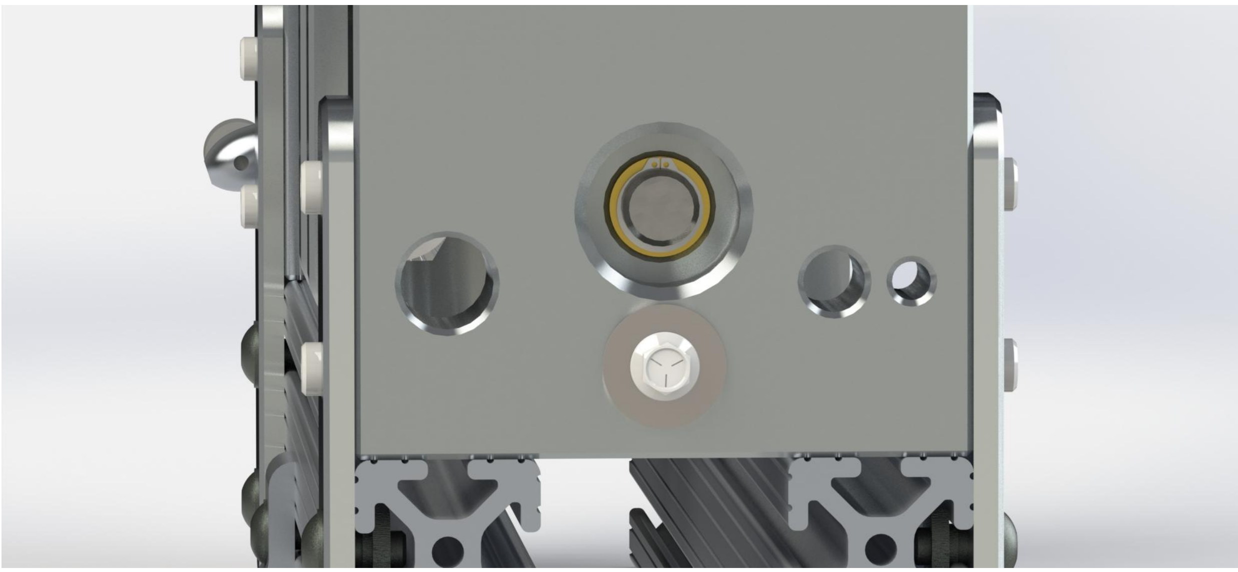


Figure 15: Outside Fixturing of Round Samples to Crossheads CAD

The samples in this design are fitted via a bolt and two-nut fastener assembly, whose threads match the sample being gripped, on each crosshead. There is a grade 8 steel bolt which is securely fastened to the crosshead (head facing away from the specimen) via a high-strength steel high-nut on the opposite side of the crosshead. The samples are threaded externally on either end and are screwed into the remaining empty length available in the high-nuts, then tightened down via the two low-nuts on either side. This subassembly can be seen below in **Figure 16**, which shows round sample 3 being gripped using 3/4” nuts and bolts.

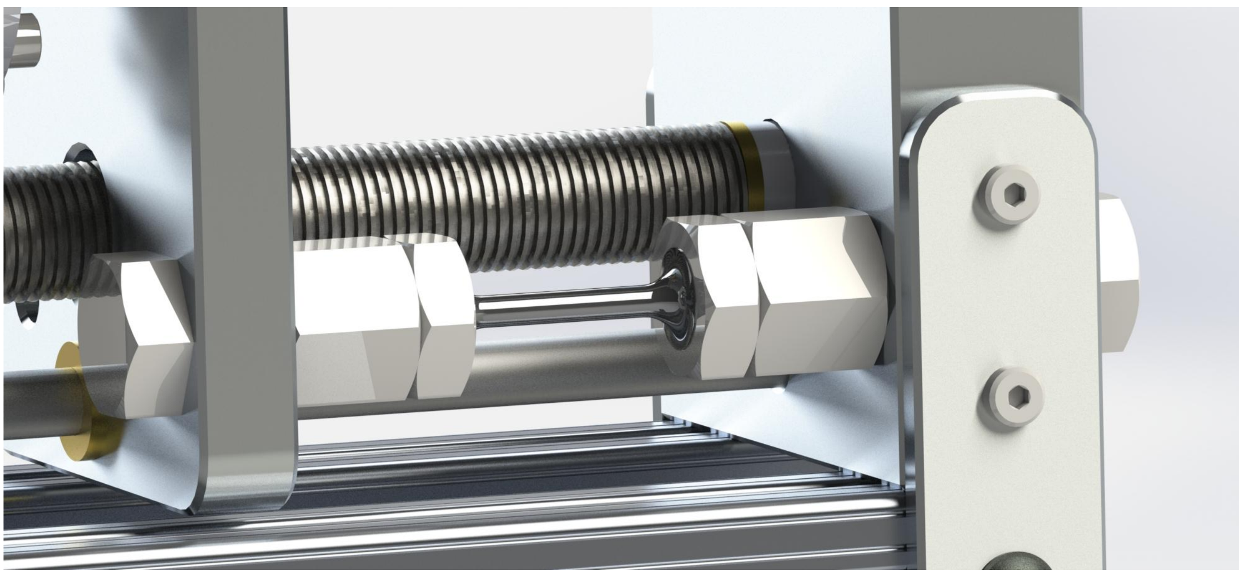


Figure 16: Round Sample Grips CAD

e. Flat Sample Grips and Testing

When testing in tension, research showed the best types of grips for the ASTM E8 standard are wedge grips due to their self-tightening ability and ease of securing specimens [13] [5]. To meet the needs of the materials tester forces, the grips need to be rated for up to 5kN of applied force. Pricing of these grips at this rating range from roughly $500 and can go into the thousands, so the team had to manufacture these grips in order to achieve the budget goals for this project. In order to properly grip the test specimens the wedge grips are faced with a diamond serrated pitch and have a maximum opening of roughly 0.3”. These grips, shown in **Figure 17** below, are 1”x3”x5”, manufactured from 1018 cold-rolled steel, and have tool steel grips to clamp flat specimens.

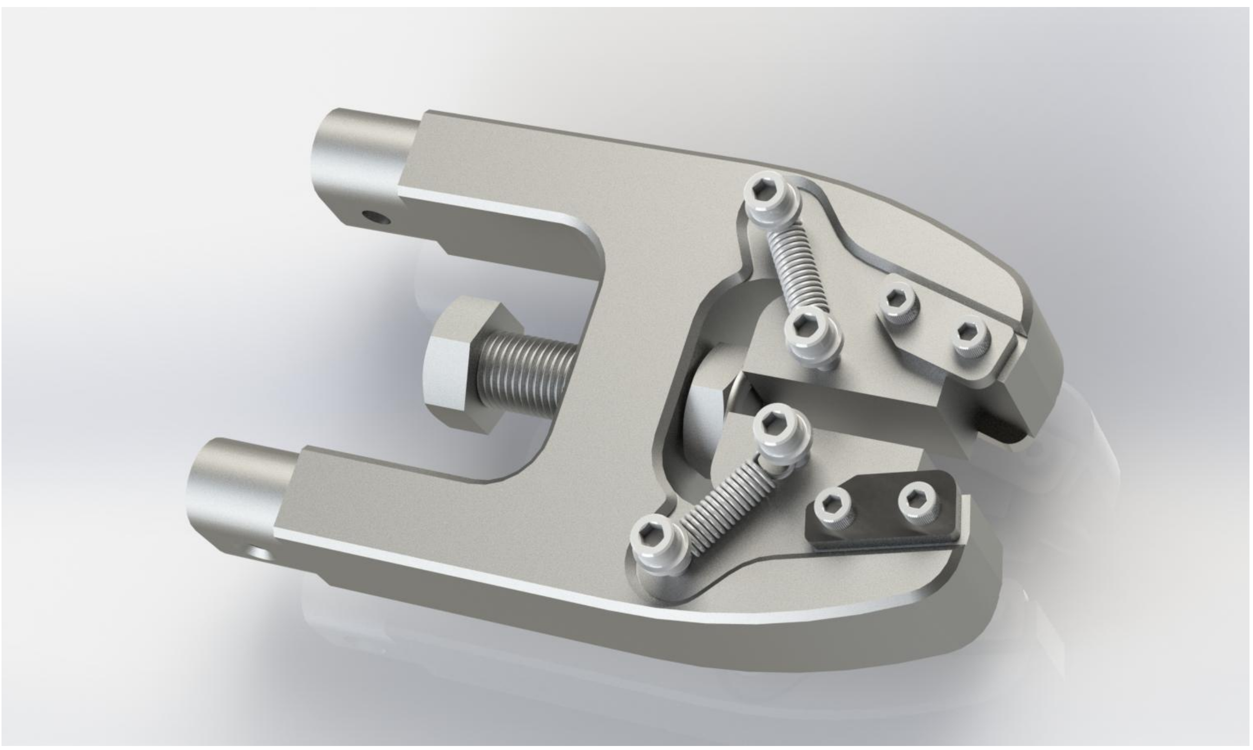


Figure 17: Flat Sample Grips CAD

f. Compression Grips and Testing

When designing grips for compression testing, the team followed the ASTM E8 standard. The main limits when designing these grips were that polymers need to be tested with a minimum square or circular cross-sectional area of $4in^2$ and the materials tester is mainly used horizontally. With that in mind, the designed grips shown in **Figure 18** have a 2”x2” pocket so material cannot slip during testing. These grips would be able to comfortably fit between the linear motion rods and are planned to be manufactured from cold-rolled steel. A second compression grip is supposed to go on the opposite side of the testing area when used horizontally so the specimens can be properly supported.

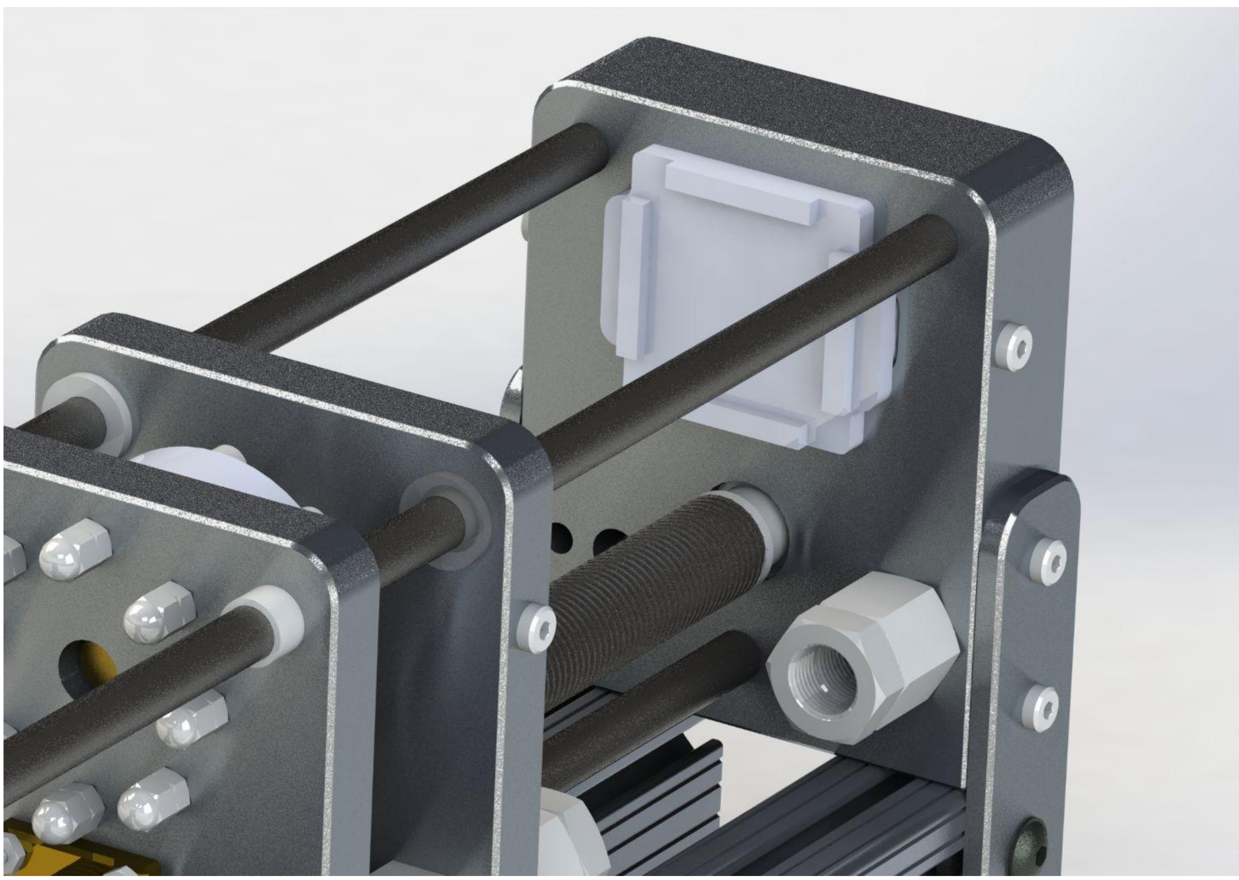


Figure 18: Compression Grips CAD

g. Wire Sample Grips and Testing

Another goal of the materials tester was to have the ability to test various wire specimens. Wires make great test specimens because they are widely available for a large selection of materials and are already of uniform diameters that can be compared to one another. The goal of the design was to develop a wire testing grip that threads into the largest round specimen sample. In this way, it would not be necessary to have a significant amount of additional space on the machine to test these samples. Below is a possible design of a wire testing grip that could be used on the machine, taking advantage of its modularity.

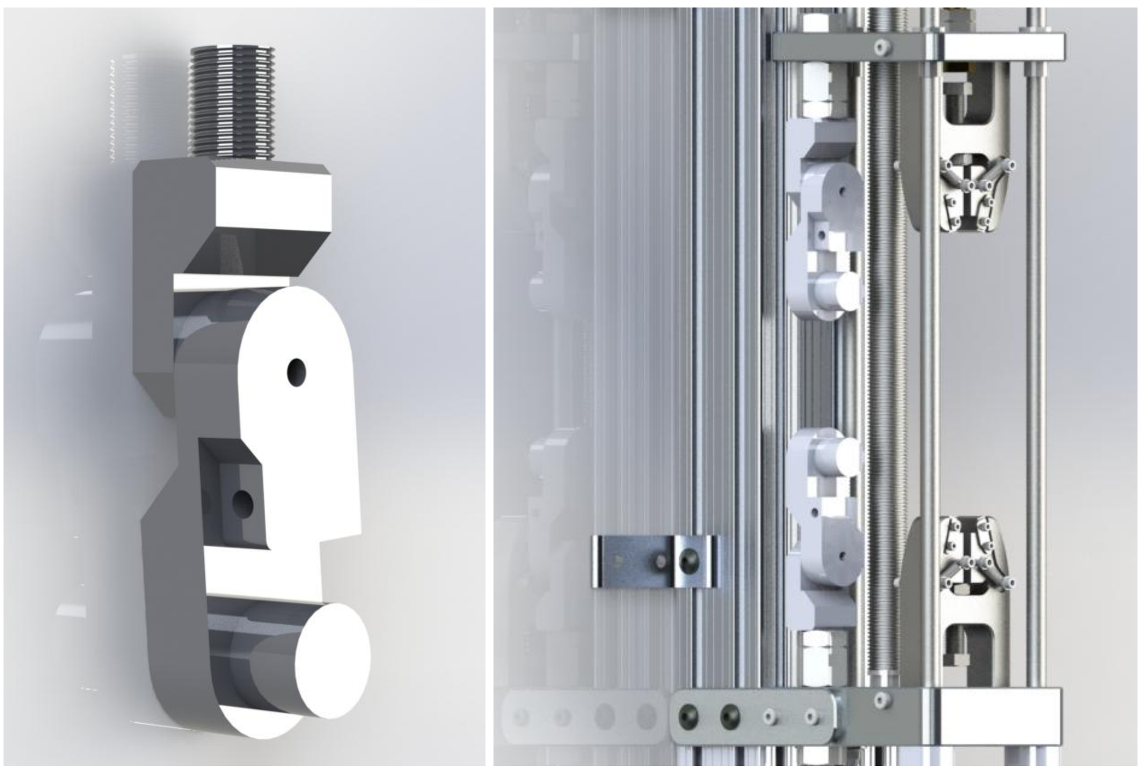


Figure 19: Preliminary CAD Design of Wire Sample Grips

h. Three-Point Bending Sample Grips and Testing

An additional goal when designing this materials tester was the ability to test materials in three-point bending. The team wanted these grips to be easily machined and be able to be used in both horizontal and vertical orientations. The designed stationary bending grip is composed of five metal pieces and six fasteners, and the moving piece has two metal pieces and two fasteners. The planned three-point bending grips are pictured below.

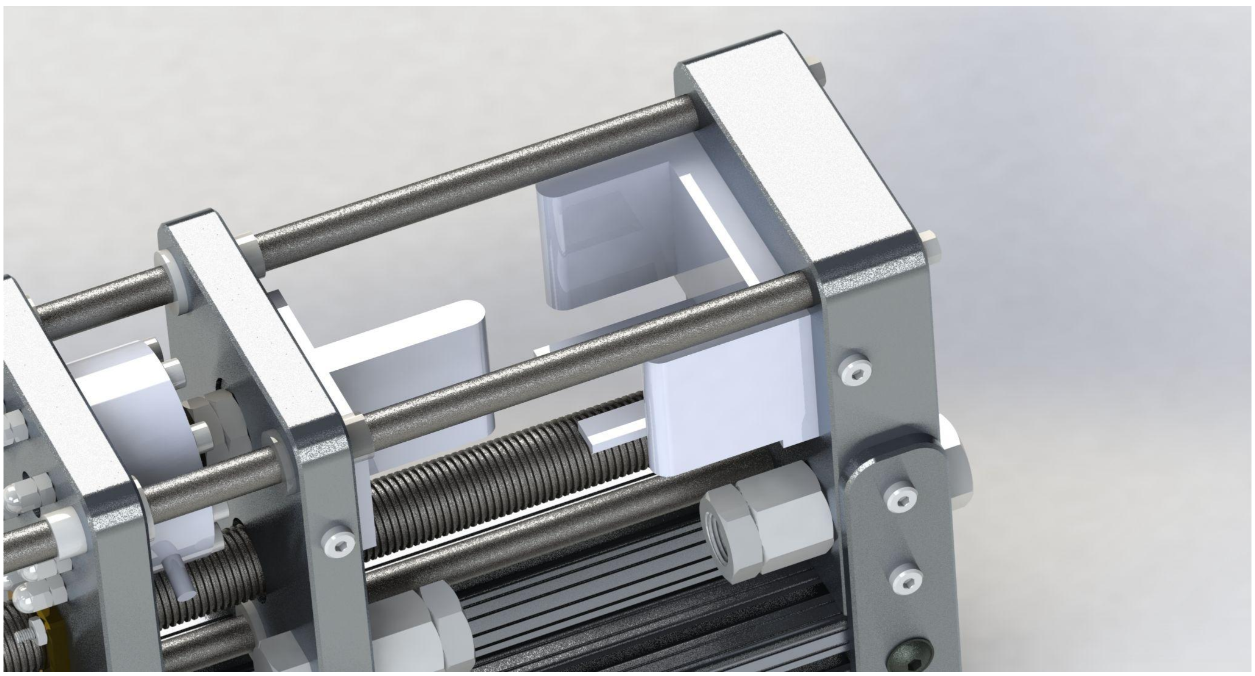


Figure 20: Preliminary CAD Design of Three-Point Bending Grips

i. Driving

It was evident that in order to reduce costs for these universal materials testers, the team would not be able to use a motor to apply the torque on the lead screw. With that in mind, the idea of using a gear reduction to generate more torque was floated. While this would allow for the creation of a much larger torque, there were several issues with this idea, the largest being the creation of the gear. Furthermore the addition of gears presented a much higher materials cost and additional design work. A calculation was done to determine the required torque for the chosen 1”-10 lead screw to exert the desired 600lbs of force. As shown in **Figure 21** below, this calculation found the necessary torque value was 78in-lbf. This value was then used to determine the minimum crank length, and it was found a crank with a 6” radius would work comfortably. For this reason it was determined the addition of gears were not needed.

F=force, d=diameter, l=inches/thread, μ=coefficient of friction, α=thread angle/2

$$\frac{Fd}{2}\left(\frac{l + \pi\mu d \sec\alpha}{\pi d - \mu l \sec\alpha}\right) = Torque$$

$$\frac{600 * 0.95}{2}\left(\frac{0.1 + \pi * 0.23 * 0.95 * \sec(14.5)}{\pi * 0.95 - 0.23 * 0.1 * \sec(14.5)}\right) = 77.9$$

Figure 21: Calculation of Torque Required for 600lbs of Force

The crank itself was also something that needed to be discussed at length. The design, which can be seen in **Figure 22** below, features two rotating handles for easier turning and is fitted to the lead screw via a tapered pin through both the screw and the handle. The taper pin provides enough strength to handle the torque of the lead screw while also allowing easy disassembling. The original circular design was discarded to save costs on material and to present a more ergonomic look. The two handles themselves and the cap were designed to be machined and turned from a 1” rod and made as three separate pieces.

They were to be joined together via MIG welding and the rotating polymer handles simply threaded into the ends of the handle.

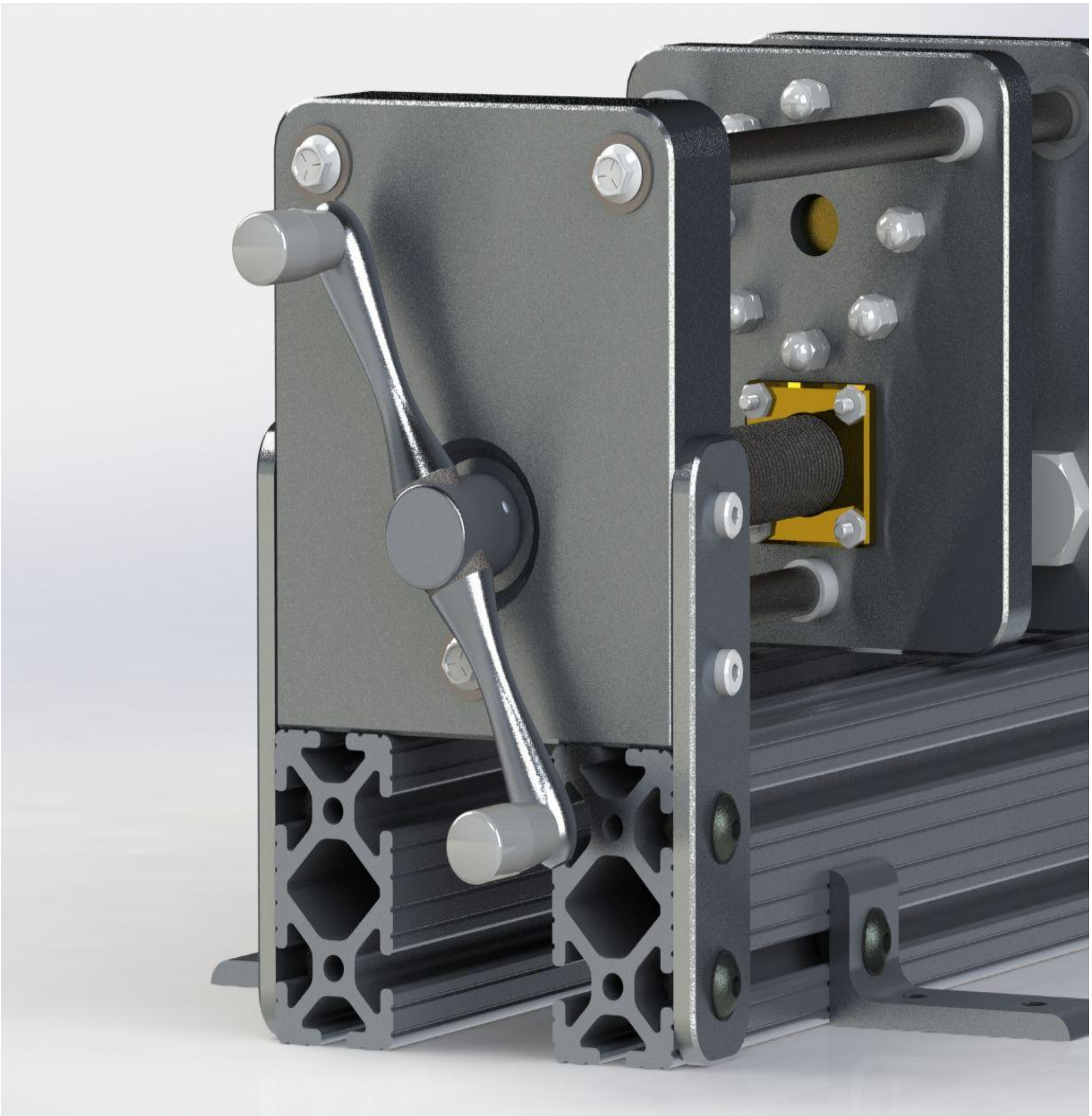


Figure 22: CAD Crank Assembly

IV. Implementation

The following chapter will detail the implementation of the aforementioned design choices and their iterations in order to realize the development of a feasible prototype universal materials tester. In the end, this resulted in an average cost per machine of roughly $520 subject to available materials, shipping, and other factors. Note that $520 reflects the average cost between the team's raw price per assembly and the price paid per assembly, as a lot of assembly materials can be found or already available in many academic and STEM settings.

As part of the implementation and realization of the machine, the project produced a comprehensive operational package accessible to researchers, students, and machine users. This included organized CAD and CAM folders of the machine and its parts and detailed instructions on how to fabricate them, a code folder of calibration and operational code for the load cell, a folder of pertinent ASTM standards, a formal bill of materials with market links (also given in **Appendix A**), an instructions, operations, and maintenance manual, this report, the machine's materials library with properties, and finally custom-fitted standard round specimen sizes.

i. Computer-Aided Design

An attached drawing package in USB drives with Professor Levey and Daniello, and in the materials tester toolbox provides the detailing and sizing of the critical parts of the assembly of the prototype materials tester. The project's comprehensive CAD package includes .dwg and .pdf detail drawings of parts and assemblies of the materials tester, as well as the solid models and assemblies used to design, fabricate, and implement the machine.

ii. Fabrication

This section details the procedures for manufacturing the parts and other critical components of the materials tester from the available and purchased materials through brief process summaries for each parts group including milling, turning, and other machining operations. The entirety of the machining processes for the materials tester were completed on-site at WPI using the machinery available in Washburn Shops. Detailed stock, machining, and operation callouts including completed Esprit files for every critical part can be found within the operational package's comprehensive CAM folder.

a. Crossheads

The crossheads of the materials tester were machined entirely using the CNC mills (Haas MiniMill). The stock blocks of 6061 aluminum were bought close to final dimensions. A series of facing and milling operations produced the holes and chamfers on each face. A few of the crossheads had holes on the sides for frame brackets and/or grip mounts. The location of each of these holes required less precision and was drilled manually using a drill press and tapped by hand. In the future, it would be better to use the manual mill or CNC mill to do these more precisely.

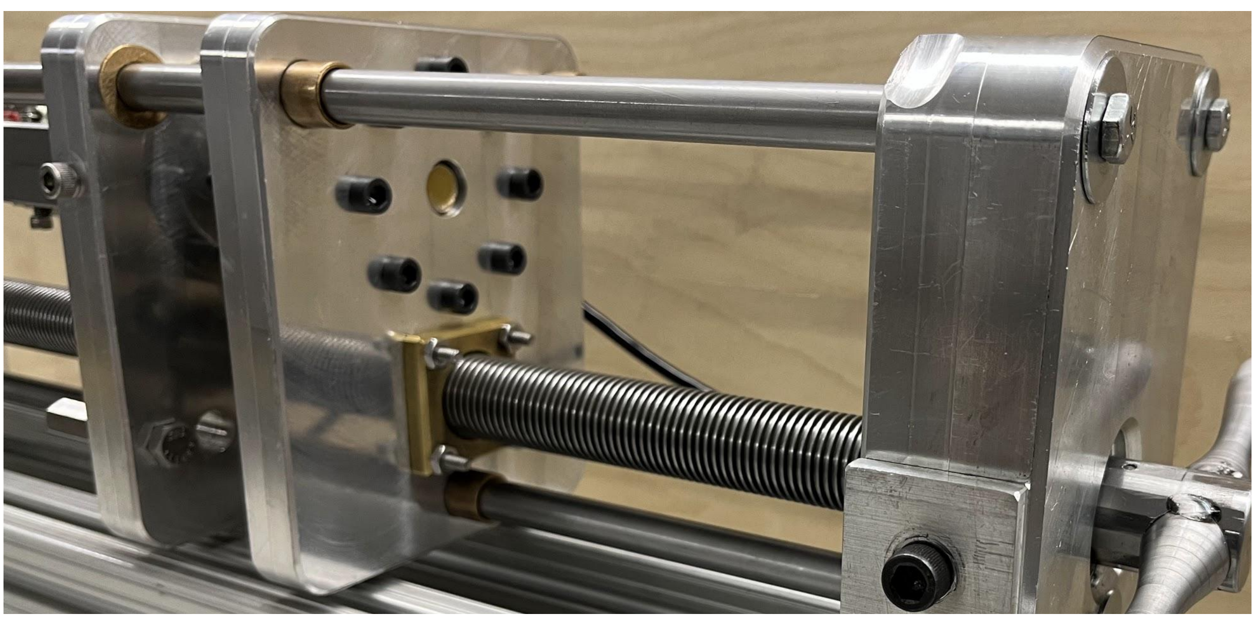


Figure 23: Crossheads

b. Frame Brackets

The frame brackets were manufactured from scrap 6061 aluminum in WPI's Washburn Shops. They were cut to size using the vertical band saw and then the manual mill was used to face the cut edges to flat surfaces and drill the holes located by the team's detail drawings.

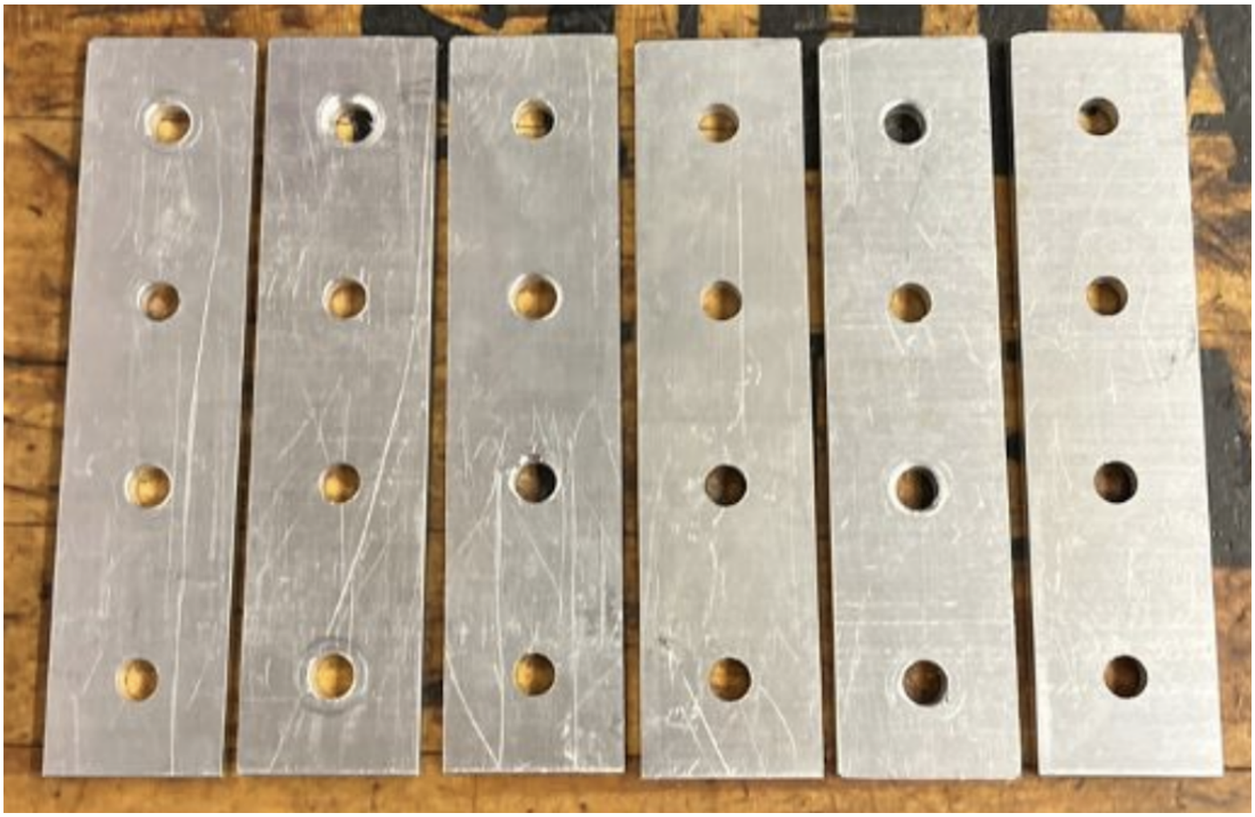


Figure 24: Frame Brackets

c. Linear Motion Rods and Bearings

The linear motion rods, made of 1045 turned, ground, and polished steel, were ordered to length. They were each loaded into the manual lathe using a collet to prevent surface damage. The manual lathe was used to drill holes in the end of each rod which was then tapped by hand. The rods were then sprayed with WD-40 and polished with a Scotch-Brite pad to improve the surface finish to allow the bronze bearings to slide more easily along them.

The bearings that were used to slide along the rod were manufactured exactly for 1/2” shaft size but needed to be pressed into the crossheads. This pressing caused the bearings to collapse in on themselves, slightly reducing their inner diameter. After pressing, a reamer was used to bring the inner diameter back to 1/2“. A file was used where needed to remove burrs on the edges of the bearings that were causing crossheads to stall horizontally. These bearings were later replaced with ball bushings as detailed further in the Assembly and Testing section.

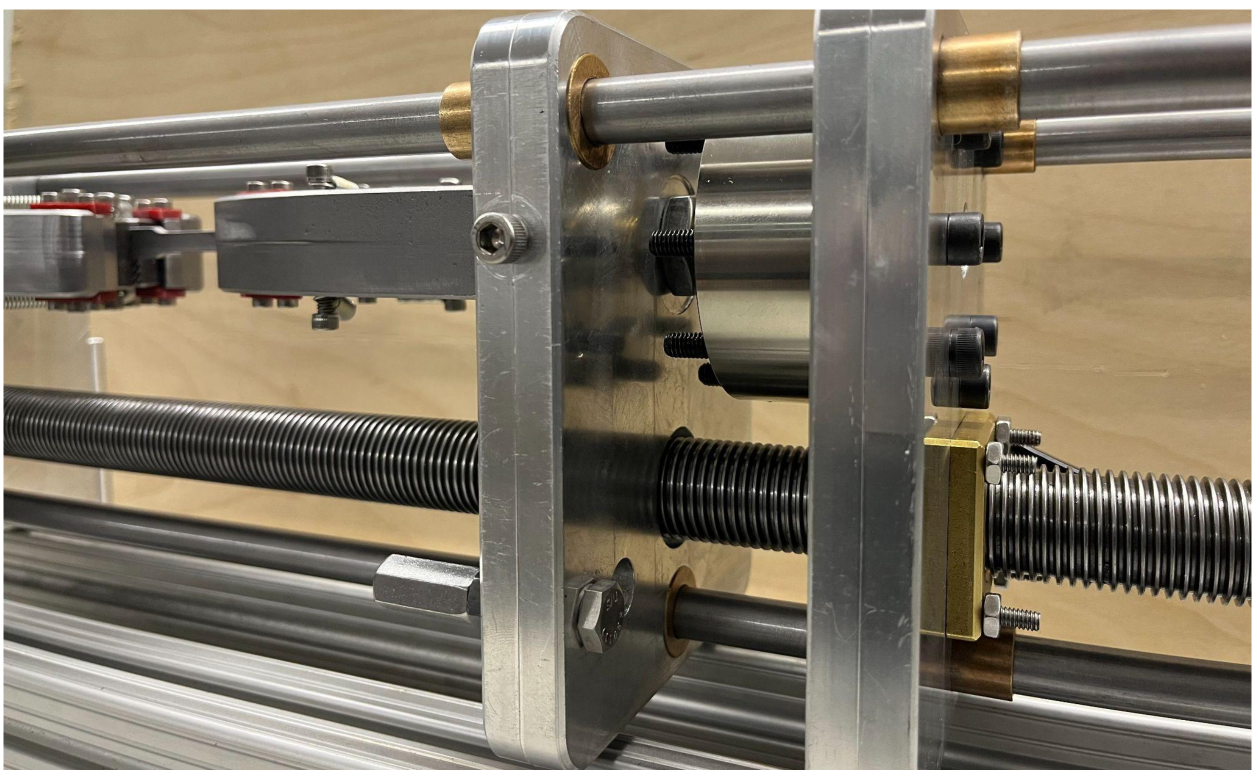


Figure 25: Lead Screw and Bearings

d. Lead Screw and Lead Screw Nut

The lead screw was relatively simple to manufacture for the tester. A six foot section of a 1”-10 Acme lead screw made of carbon steel was cut down to desired two foot segments using a chopsaw. The lead screw was then loaded into the manual lathe and the ends were turned down according to the desired design represented in detailed drawings. Grooves were also cut into the ends for the snap rings to sit. A micrometer was used to ensure tight tolerances with the bearings that the lead screw would occupy. The brass square lead screw nut was machined in a CNC mill to turn it into a flanged cylindrical nut with a square base for screw holes. These screw holes were also drilled in the mill.

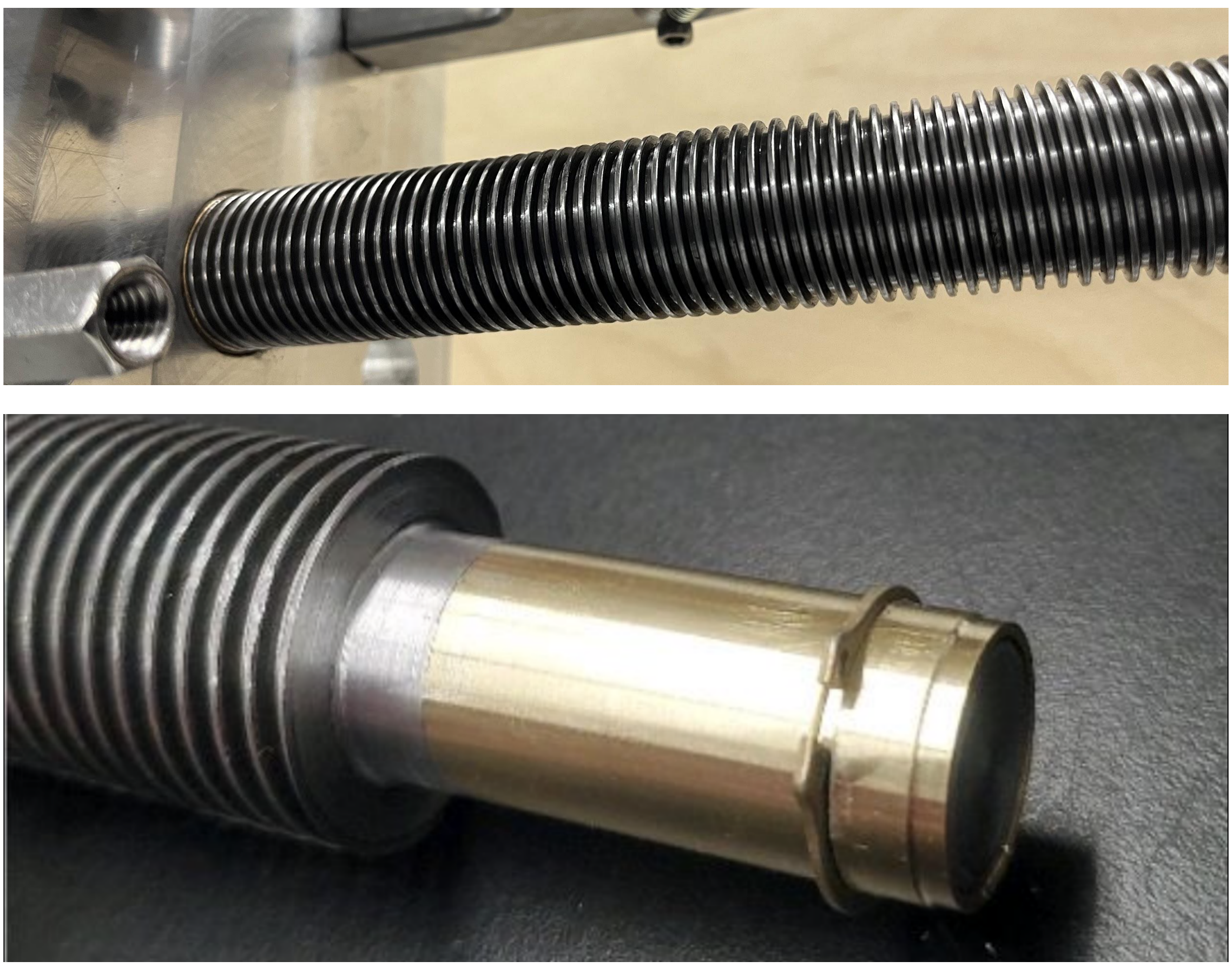


Figure 26: Lead Screw

e. Flat Grips

The flat grip assembly began with the flat grip body machined from 1018 steel bars using a series of facing, milling, and drilling operations on the CNC MiniMill. Since the part was machined from a bar stock, it was relatively simple to fixture to any face to complete the necessary operations. Finally, the team used the manual mill to drill the central 1/2-20 hole for the driving screw. The 1/2-20, 6-32, and 8-32 holes were all manually tapped.

The flat grip assembly utilizes 4041 alloy steel grips to clamp down on the flat specimen and caps to contain them. The tool steel grips were cut to size using a chopsaw and then faced, engraved (to produce a frictional, gripping surface), and contoured to size. Drilling and manual tapping were also completed to finish these parts. These grips can additionally be heat treated to harden the material for higher grade clamping applications. The flat grip caps were fabricated using fused-deposition rapid prototype modeling on a 3D printer using PETG filament, which is stronger than standard PLA and ABS options. One of these caps was also produced using sheet metal steel by grinding and drilling. Both options were feasible; however, the FDM option was much faster and more efficient, and very durable as well.

The assembly is held together with bolts and screws, with a nylon lock nut at the end of the driving screw. The tool steel grips are held in tension from extension springs which produces the desired self-tightening function. A flat grip assembly can be seen in **Figure 27** and **Figure 28** below.

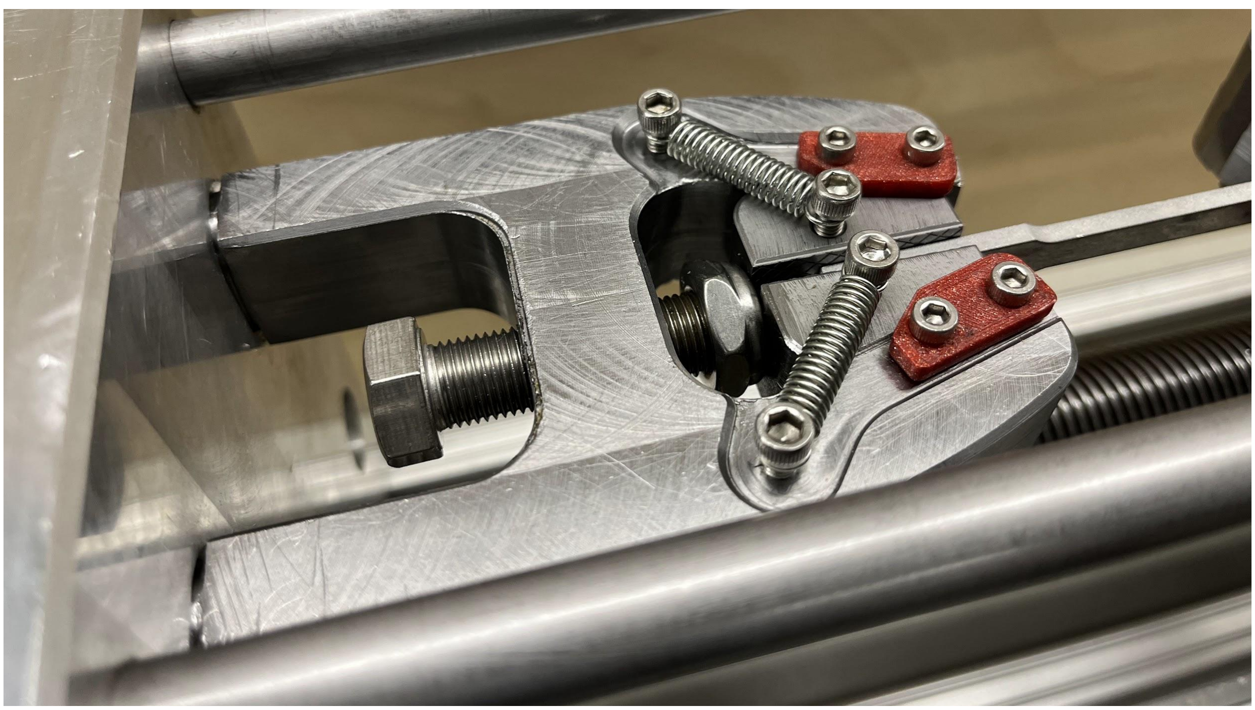


Figure 27: Flat Grip Assembly I

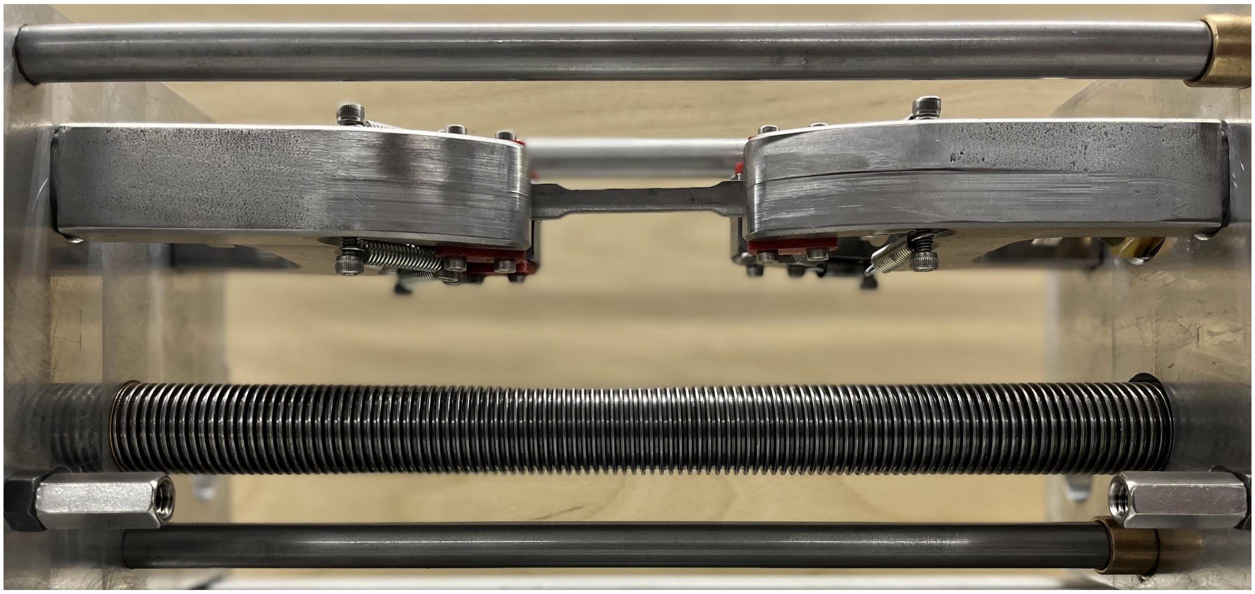


Figure 28: Flat Grip Assembly II

f. Crank

The crank for the materials tester to drive the lead screw required several steps that had to be completed in a specific order to produce the desired result. The idea was for all the pieces to be able to be machined from the same 1” stock of 1018 cold rolled steel. The crank cap, pictured below, was a challenge to fabricate as it required holes to be milled into the sides for the handles to sit in. The solution involved a total of one turning operation and six milling operations. The stock would be inserted into the lathe and the center hole bored out before the piece was then cut from the stock. The cap was then placed in the CNC MiniMill, held between the two flats of the cap. A simple facing operation took off a small amount from the top of the cap. The operation was then repeated on the opposite side creating two flats. The cap was then mounted vertically and an endmill created an octagonal contour on the outside of the cap to provide flat surfaces to vice. It was then flipped to create the shape through the part. With the eight flat sides on the cap, the drilling and counterbore operations could safely be completed on opposite sides. This also allowed for easy fixturing when creating the taper hole. The tapered hole was created in both the lead screw and the cap simultaneously using the manual mill to drill the hole at the taper pin’s smallest diameter and then using a taper reamer by hand.

The crank shafts also required a level of care when creating them in the CNC lathe. The contour and slenderness of the part made them difficult to manufacture and once machined, they would be impossible to grip in the vice due to the curved profile. For this reason, the hole and counterbore needed for the crank handles had to be done prior to the turning. This was done using the manual mill. After the holes were created, the shafts could be turned down entirely in the lathe. The lathe code was written in such a way that no finish pass was completed to reduce machining pressure, as it caused the handle to bend inside the lathe as the roughing tool touched off on the slender end of the shaft. By removing the finish pass, the end of the handle was machined before the handle was turned thinner, reducing the risk of deflection and failure.

The crank assembly was then MIG welded together using a basic spot weld on two contact tangents between the crank cap and crank shaft. The crank grips, purchased from McMaster-Carr were then inserted into the shaft and secured via Loctite.

Figure 29: Finished Crank Assembly

g. Test Specimen

The round test specimens were made using a CNC lathe (SL10). Because the specimens' smallest diameter is significantly less than their length, it was required to insert the tailstock for support before performing the thinning operation. Initially, the material only protruded out from the grip far enough to turn down and thread one side. After that, a center hole was drilled and the machine stopped to allow the material to be pulled out far enough from the grips to have room to turn and thread the other side. The tailstock was then inserted, but it was important that it didn't use more pressure than was necessary to hold the material in place. Too much pressure in the tailstock can cause the sample to break during machining.

With the tailstock in place, the lathe was resumed. The lathe turned down the middle of the sample with a right-handed tool, then switched to a left-handed tool to rough the opposite curve. Both of these operations removed smaller than normal amounts of material at a time, to ensure the sample didn't break while it was being thinned. The far side was then turned and threaded, and the finished round sample was cut off from the rest of the stock material to complete the specimen. The threads of the round sample also required slight die-tapping to clean any imperfections and burrs in the process to allow for smooth fixturing.

Figure 30: Round Specimen 5

iii. Assembly and Testing

The following section will summarize the final assembly, troubleshooting, and realization of the machine, and how the team was able to produce an effective materials tester prototype through the steps taken in the design and fabrication phases. The team produced an instructions, operations, and maintenance manual - a detailed guide on the assembly - which can be found within the project's operational package.

When assembling the prototype, the team encountered several issues that prevented the machine from operating correctly. Many of these issues can be drawn back to the Acme lead screw which contained a significant bend from the manufacturer. The problem was discovered late in the testing phase which did not allow for much time to remedy the situation. Rather than try and straighten the lead screw, the brass square nut was turned down slightly allowing it to slightly wander inside the crosshead as the lead screw moved up and down. This solved the problem of the stiffness in the lead screw but the increased slop in the brass nut made the driving crosshead (RightMidCrosshead) have a tendency to bind on the linear motion rods.

The bronze oilite bearings that were chosen to slide on the lead screw required a lot of troubleshooting to get them to work. After they were initially pressed into the crossheads, they collapsed in on themselves slightly and needed to be reamed out back to their true size. This resulted in a lot of back and forth reaming and testing and filing to try to get a snug fit that was free enough to slide with as little slop as possible. Even after the bearings appeared to be working as intended, they never were as free sliding as hoped. They had a very high static friction which became a real problem when the lead screw was used to move the crossheads. The crossheads kept binding on the linear motion rods and wouldn't even move under their own weight.

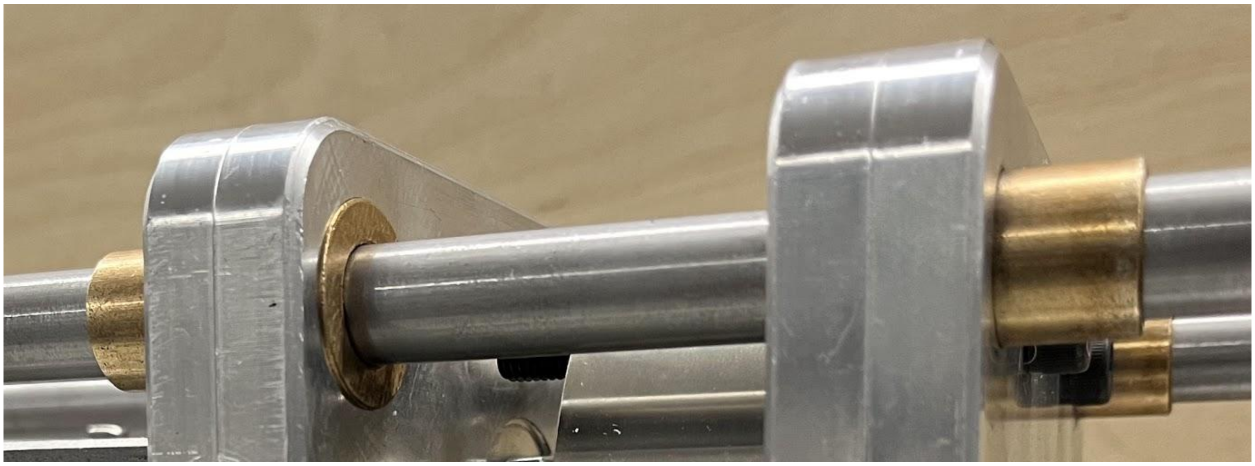


Figure 31: Bronze Oilite Bearings on Linear Motion Rods & Crossheads

Ultimately the team decided to scrap the bronze oilite bearings and use linear ball bearings instead. These bearings are significantly more expensive but they are self-aligning and could handle the movement created by the bent lead screw (these particular bearings can correct up to a 0.5° misalignment). However, these bearings are larger than the original bearings so the bottom of the square nut had to be ground down to make room. In addition, these new bearings are thicker, so a washer was used to take up the extra space between the snap ring and the crosshead (alternatively, the crosshead could have been made thicker to accommodate this change). This adjustment allowed for the desired free, unimpeded movement of the crossheads as the lead screw was cranked.

Figure 32: Self-Aligning Ball Bearing

The current capabilities of the machine for the load cell use time as a variable for determining strain, where the amount of time needed to rotate the crank by a given number of revolutions corresponds to a strain value (translated distance of crossheads along the lead screw) and to a readout interval on the machine's microcontroller. This is less than ideal for generating a precise stress-strain curve. The absence of a strain gauge on the machine made it difficult to generate meaningful data in its current state and is something that needs to be addressed in the future. The team found, through machine assembly and testing, that a consistent and accurate stress-strain curve is best produced when strain is a much more controlled and steady variable in the test than originally estimated. These steady and less noisy graphs are often attributed to either constant crosshead translation or sufficiently accurate extensometer readings or measurements from other instruments like strain gauges implemented in concert with a given material specimen. Because the cranking of the machine wasn't precisely constant, the rate at which the crossheads translate wasn't either, resulting in the strain not being constant with the time-based measurement intervals of the team's microcontroller. Ultimately, the strain readings of the tests need more accurate and improved means of measurement.

V. Results:

The following section details the results of the project and the current state of the machine and its various components at the conclusion of the academic year.

The list of components including raw material, hardware, and fasteners can be found in **Appendix A**.

i. Prototype

The materials tester prototype was unsuccessful in breaking the produced round specimen of mild steel. While the crossheads were able to translate freely while unloaded, when the specimen was attached, the crosshead that was not corrected with ball bearings replacing the original bronze bushings was binding against the linear motion rods. Another set of ball bearings have been ordered with the hopes of remedying the issue entirely for all moving crossheads. The team believes that replacing the other three (other half) of bronze bearings embedded in the remaining middle crosshead (LeftMidCrosshead) with ball bearings will entirely prevent any binding issues as experienced earlier. While the specimen did not break, the machine was successful in applying a significant load to the specimen which may have been strong enough to break a weaker polymer specimen had one been fabricated and available.

ii. Testing Grips

The original objective of the materials tester was to be able to test both flat and round specimens in tension, and different specimens in compression as well as complete three-point bending tests and wire tensile tests. The grips for the three sizes of round specimens were completed, although slight changes in fixturing bolt lengths might be required to improve ease of use. The flat sample grips were also completed and are shown in **Figure 33** below**.** Due to the length of time and detail in fabrication needed to machine the parts, only two of the tool steel grips were produced. Material is available to produce more, and the CNC programming to produce more is also completed. After all the tool steel grips are completed it is recommended to heat treat the surface of the grips before they are used for testing. The resulting increase in hardness should prevent damage while testing and increase part life. The wire grips, the three-point bending grips, and the compression grips were not produced, however detailed CAD files for the models are contained in the operational package for future manufacturing and production.

Figure 33: Completed Flat Sample Grips

iii. Load Cell and Measurement

The load cell was calibrated with a simple setup utilizing a vice, string, and a 10N spring scale. Varying known forces were applied in both tensile and compressive directions, and the calibration factor was then recorded. After, the calibration factors were incorporated into the operational code and package as tested.

During testing the load cell was successful in providing a force readout that increased as load was applied to the specimen. The data produced was not incredibly useful in its current state as the machine only produced force values with respect to time. It is therefore necessary to incorporate a way to measure strain and elongation so that useful curves such as a stress-strain curve can be produced.

VI. Discussion

The following subsections detail overall reflections after the project was finished. They give recommendations for future project teams, the impacts of this project, and the conclusions drawn from it.

i. Recommendations for Future Work

The lessons learned from the prototype have led the team to propose the following recommendations to be incorporated in the future development of the machine. An important development would be the addition of a strain gauge or basic extensometer to measure strain. The load cell allows for the recording of stress in the sample, so if the device could also measure strain it would be able to generate a stress-strain curve. Also, the code could be packaged into a stand-alone application so that the Arduino IDE is no longer required. The device could even be given a small interface so an entirely separate computer or laptop isn't required.

Another way to improve the machine would be to add a second lead screw connected by a chain and sprocket. While this would increase the cost of the device, one of its most significant issues right now is the crossheads rotating instead of translating due to the imperfections in the straightness of the lead screw, causing the crossheads to bind. If the machine were to be made wider or taller and a second lead screw installed so the samples and load cell were between the two lead screws, then the crossheads would no longer be attempting to rotate and exert unwanted force on the linear motion rods. While it would increase the number of parts, this would make the device much more reliable, accurate, and easy to use. The crossheads could simply 'float' along the lead screws and actually reduce the number of structural linear motion rods as more lead screws are introduced. Another way to potentially combat the issue of the crossheads deflecting would be to get additional or thicker linear motion rods to stabilize any bending or deflection across the face of the crossheads. While the current 1/2" rods are stiff on their own, they bend quite easily when being driven by such a large lead screw. More linear motion rods located near the bottom of the crosshead would help combat this issue.

Another recommendation would be to make the crank handle longer to generate more torque. Note that this added torque would not be a solution to the binding, the ball bearings are the recommended solution to that; added torque would simply improve user friendliness and ease of use. The team's current design was limited by the location of the lead screw and the fact that the height of the lead screw off the table or operating surface would dictate the maximum radius of the crank such that it (or the user's hands) wouldn't make contact with the table during rotation. Adding a motor to rotate the lead screw at a constant rate could also help user-friendliness, despite adding to the cost of the machine; this could also help with the stabilization of rotations versus time to help determine accurate time-based strain values to correlate to exact stress values. There is room for added costs, so a motor may be a worthwhile investment, especially when considering the manufacturing times and costs of the crank being eliminated (roughly -$28.71).

There are also a few smaller changes that should be made for easier operation and to improve functionality. The smallest round sample holes in the crosshead should be relocated, allowing all the hardware to test multiple sizes of round specimens to be mounted at the same time, saving time to interchange parts and samples if testing multiple round specimens. The team also had difficulties when securing round specimens. After looking through why this is, the team found that if the nuts holding the round specimens were not simultaneously running on the studs from the crosshead, they would be much easier to install. Another change is in the rectangular frame brackets. If they were adjusted to be an "L"-shape and not extend to the lower level of the 80/20, the mounting feet could easily be loosened and removed to be reused for scenarios when the machine is operated vertically (if the feet were fabricated). This would remove the necessity to have extra frame brackets needed for this purpose. In addition, the length of the round sample mounting bolts could be increased to be able to secure more threads on the round specimens.

Overall, this project has the potential to be a very useful tool in engineering education applications, thus the realm for changes to adapt and develop this materials tester can be vast due to the machine's modularity and detailed documentation over the course of the academic year.

ii. Broader Impacts

By developing a means to inexpensively produce an easy-to-use universal materials tester with basic CNC machinery and hand-tools entirely from scratch, this project has paved the way to increase the accessibility of such devices in classrooms, labs and workshops. Using the machine, undergraduate students in mechanical and materials engineering classes will be able to gain a hands-on understanding of how the stress-strain curves in their textbooks were produced. If a lab or workshop requires material testing, but the machine's ability to demonstrate the processes are prioritized over high accuracy, this machine is an extremely cost-effective and efficient alternative to the very expensive materials testing machines already on the market at a very affordable price of around $520 per machine. This machine also has a far lower space requirement and hardware - while common commercial materials testers usually have to be installed into a lab, the device fits on a standard benchtop work surface and can be removed and placed into storage when not in use. Ultimately, this materials tester developed over the course of this academic year not only provides value in terms of producing tangible material property data, but also cultivates the overall learning and hands-on approach towards experimentation within the mechanical and materials engineering curriculum and scholarship.

VII. Conclusion

In this major qualifying project an inexpensive benchtop universal materials tester was designed, fabricated, and assembled entirely from scratch. The design process involved detailed CAD and tolerancing, with multiple design iterations. The machine was manufactured using CNC and manual machinery, and this included creating and executing fabrication programs in Esprit as well as many assembly tweaks and troubleshooting processes. The materials tester prototype was completed and was able to apply a tensile load to either a round or a flat specimen, and the loads could be measured with the load cell. However, a bent lead screw caused the crossheads to bind, so the round steel test specimen could not be loaded to its fracture stress. Recommendations were provided for resolving this defect in future iterations.

A user manual was written for future users and includes maintenance instructions and code needed to operate the load cell. Detailed documentation has been provided for future teams, including CAD and CAM files, with insights on design improvements for a beta prototype. The design is modular, and future teams have the ability to incorporate compression, wire, and bending capabilities.

Ultimately, the team believes that continuations and future developments on this materials tester possess a significant capacity to foster and inspire valuable classroom learnings within pertinent STEM disciplines at WPI and the broader academic settings beyond for years to come.

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Appendix

Appendix A: Materials Tester Bill of Materials and Cost

	Iteration Assembly Costs per 1 Assembly	AliExpress ; Midwest Steel ; McMaster-Carr ; 80/20 ; Arduino				
Class	**Member**	**Market Link**	**Usage**	Qty	Price/1 Asmbly	Paid/1 Asmbly
Hardware	AliExpress Load Cell	https://www.aliexpress.com/item/32803442545.html?spm=a2g0o.productlist.0.0.15907e8e6dRr0O&algo_pvid=71796100-8b15-44a2-8670-cc7440f720a9&algo_exp_id=71796100-8b15-44a2-8670-cc7440f720a9-0&pdp_ext_f=%7B%22sku_id%22%3A%2266296624998%22%7D	Load Cell	1	$50.99	$50.99
Raw Material	Carbon Steel Acme Lead Screw Right Hand, 1"-10 Thread Size, 6 Feet Long	https://www.mcmaster.com/98935A219/	Lead Screw	1	$15.19	$15.19
Raw Material	360 Brass Acme Square Nut Right Hand, 1"-10 Thread Size	https://www.mcmaster.com/95270A155/	Brass Lead Screw Nut	1	$26.62	$26.62
Fastener	18-8 Stainless Steel Button Head Screw 8-32x1.25”	https://www.mcmaster.com/92949A201/	Lead Screw Bolt	4	$0.59	$0.59
Fastener	18-8 Stainless Steel Hex Nut 8-32 Thread Size	https://www.mcmaster.com/91841A009/	Lead Screw Nut	4	$0.20	$0.20
Fastener	LS- (50)External Retaining Ring for 5/8" OD, Zinc Yellow-Chromate-Plated Spring Steel	https://www.mcmaster.com/98410A126/	Lead Screw Retaining Ring	2	$10.00	$10.00
Fastener	Ultra-Low-Friction Oil-Embedded Sleeve Bearing Flanged, for 5/8" Shaft Diameter and 13/16" Housing ID, 1.25" Long	https://www.mcmaster.com/1677K355/	Lead Screw Bearings	2	$9.36	$9.36
Raw Material	1045 Turned, Ground, and Polished Bar	https://www.midweststeelsupply.com/store/1045turnedgroundandpolishedbar	Linear Motion Rods	3	$13.83	$13.83
Raw Material	1018 Cold Roll Steel Flat Bar	https://www.midweststeelsupply.com/store/1018coldrollsteelroundbar	Crank Raw Material	1	$6.00	$6.00
Raw Material	6061 Aluminum Flat Bar	https://www.midweststeelsupply.com/store/6061aluminumflatbar	End Crossheads	2	$47.04	$47.04
Raw Material	6061 Aluminum Flat Bar	https://www.midweststeelsupply.com/store/6061aluminumflatbar	Mid Crossheads	2	$25.06	$25.06
Raw Material	1018 Cold Roll Steel Flat Bar	https://www.midweststeelsupply.com/store/1018coldrollsteelflatbar	Flat Grip Bodies	2	$24.08	$24.08
Hardware	Ultra-Low-Friction Oil-Embedded Sleeve Bearing Flanged, for 1/2" Shaft Diameter and 5/8" Housing ID, 1-1/4" Long	https://www.mcmaster.com/1677K342/	Linear Motion Rod Bearings	6	$16.56	$16.56
Hardware	Steel USS Washer for 1/4" Screw Size, 0.312" ID, 0.75" OD	https://www.mcmaster.com/91081A129/	Linear Motion Rod Washers	6	$0.32	$0.32
Hardware	Zinc-Plated Grade 5 Steel Flanged Hex Head Screws Medium-Strength, 1/4"-20 Thread Size, 1/2" Long	https://www.mcmaster.com/92979A110/	Linear Motion Rod Screws	6	$0.86	$0.86
Raw Material	80/20 No. 1530-S 24" Long 15 Series	https://8020.net/1530-s.html	80/20 Base Frame	2	$59.44	$0.00
Raw Material	80/20 No. 4305 Flat Plate 15 Series	https://8020.net/4305.html	Frame Brackets	4	$23.56	$0.00
Fastener	80/20 Bolt Assembly No. 3320 5/16-18x.687"	https://8020.net/3320.html	Fastener Assembly for Frame Brackets	12	$8.88	$0.00
Hardware	80/20 No. 4376 3 Hole Corner Bracket	https://8020.net/4376.html	Side L Bracket for Bolting and Vicing	4	$19.76	$0.00
Hardware	Arduino Uno Rev 3	https://store-usa.arduino.cc/products/arduino-uno-rev3	Arduino for Electrical Output Interpretation	1	$23.00	$0.00

Class	Member	Market Link	Usage	Qty	Price/1 Asmbly	Paid/1 Asmbly
Hardware	SparkFun Load Cell Amplifier - HX711	https://www.amazon.com/dp/B079LVMC6X?psc=1&ref=ppx_yo2_dt_b_product_details	Load Cell Amplifier	1	$4.21	$4.21
Fastener	Steel Hex Nut Medium-Strength, Class 8, M6 x 1 mm Thread	https://www.mcmaster.com/90592A016/	Load Cell Bolt Circle Nuts	8	$0.25	$0.25
Fastener	18-8 Stainless Steel Cap Nut M6 x 1 mm Thread	https://www.mcmaster.com/94000A038/	Load Cell Bolt Circle Cap Nuts	8	$2.04	$2.04
Fastener	Zinc Yellow-Chromate Plated Steel Hex Head Screw, High-Strength, M16 x 1.50 mm Thread, 80 mm Long, packs of 1	https://www.mcmaster.com/91052A125/	Load Cell Button	1	$5.53	$5.53
Fastener	Black-Oxide Alloy Steel Socket Head Screw M6 x 1 mm Thread, 60 mm Long, Fully Threaded	https://www.mcmaster.com/91290A207/	Load Cell Bolt Circle Screws	8	$8.83	$8.83
Fastener	Steel Thin Hex Nut, M16 x 1.50 mm Thread Size, packs of 10	https://www.mcmaster.com/90370A106/	Load Cell Button Nuts	1	$9.14	$9.14
Fastener	Button Head Hex Drive Screws Zinc-Plated Alloy Steel, 5/16"-18 Thread, 1-1/2" Long	https://www.mcmaster.com/91306A410/	1.50 Side Bracket Screws	4	$2.22	$0.00
Fastener	Button Head Hex Drive Screws Zinc-Plated Alloy Steel, 5/16"-18 Thread, 1-3/4" Long	https://www.mcmaster.com/91306A287/	1.75 Side Bracket Screws	4	$2.39	$0.00
Fastener	18-8 Stainless Steel Socket Head Screw 6-32 Thread Size, 5/16" Long	https://www.mcmaster.com/92196A145/	Flat Sample Assembly 6-32 Screws	8	$0.33	$0.33
Fastener	Steel Extension Spring with Loop Ends, 1" Long, 0.25" OD, 0.029" Wire Diameter	https://www.mcmaster.com/9654K108/	Flat Sample Extension Springs	8	$6.00	$6.00
Fastener	18-8 Stainless Steel Socket Head Screw 8-32 Thread Size, 7/16" Long	https://www.mcmaster.com/92196A193/	Flat Sample Assembly 8-32 Screws	8	$0.55	$0.55
Fastener	18-8 Stainless Steel Hex Head Screw 1/2"-20 Thread Size, 1-3/4" Long	https://www.mcmaster.com/92240A436/	Flat Sample Driving Screw	2	$1.86	$1.86
Fastener	18-8 Stainless Steel Thin Nylon-Insert Locknut 1/2"-20 Thread Size	https://www.mcmaster.com/90101A255/	Flat Sample Driving Nut	2	$1.56	$1.56
Raw Material	Multipurpose 4140 Alloy Steel Bar 1" Thick, 1-1/4" Wide, 1/2 Foot Long	https://www.mcmaster.com/6554K55-6554K555/	Tool Steel Grips	1	$15.43	$15.43
Raw Material	Impact-Resistant Polycarbonate Rod 3/4" Diameter 1 foot	https://www.mcmaster.com/85485K45/	Round Sample 3 Raw Material	1	$8.87	$8.87
Fastener	Steel High Hex Nut Grade 8, 3/4"-16 Thread Size	https://www.mcmaster.com/90565A340/	Round Sample 3 High Nut	2	$3.10	$3.10
Fastener	High-Strength Steel Thin Hex Nuts-Grade 8 3/4"-16 Thread Size	https://www.mcmaster.com/92052A250/	Round Sample 3 Low Nut	2	$2.00	$2.00
Fastener	18-8 Stainless Steel Hex Head Screw 3/4"-16 Thread Size, 1-1/4" Long	https://www.mcmaster.com/92240A378/	Round Sample 3 Low Bolt	1	$2.07	$2.07
Fastener	18-8 Stainless Steel Hex Head Screw 3/4"-16 Thread Size, 2" Long	https://www.mcmaster.com/92240A382/	Round Sample 3 High Bolt	1	$2.41	$2.41
Raw Material	Impact-Resistant Polycarbonate Rod 1/2" Diameter 1 foot	https://www.mcmaster.com/85485K43/	Round Sample 4 Raw Material	1	$4.73	$4.73
Raw Material	Low-Carbon Steel Rod 3/8" Diameter	https://www.mcmaster.com/8920K135-8920K519/	Round Sample 5 Raw Material	1	$4.93	$4.93

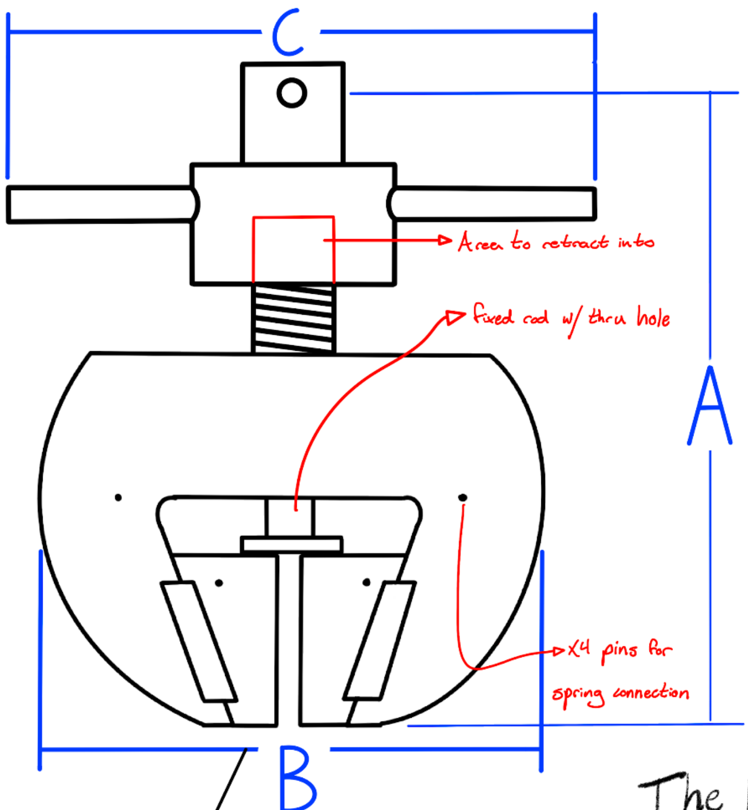
Class	Member	Market Link	Usage	Qty	Price/1 Asmbly	Paid/1 Asmbly
Fastener	Mil. Spec. High-Strength Steel Hex Nut Cadmium Yellow-Chromate Plated, 1/2"-20 Thread, MS51968-15	https://www.mcmaster.com/94191A550/	Round Sample 4 Nuts	6	$5.68	$5.68
Fastener	18-8 Stainless Steel Hex Head Screw 1/2"-20 Thread Size, 1-1/4" Long	https://www.mcmaster.com/92240A434/	Round Sample 4 Low Bolt	1	$0.71	$0.00
Fastener	Zinc-Plated Steel Coupling Nut Low Strength, 1/2"-20 Thread Size, 1-1/4" Long	https://www.mcmaster.com/90264A117/	Round Sample 4 Coupling Nut	2	$2.30	$2.30
Fastener	18-8 Stainless Steel Hex Head Screw 1/2"-20 Thread Size, 2" Long, Fully Threaded	https://www.mcmaster.com/92240A437/	Round Sample 4 High Bolt	1	$0.61	$0.00
Fastener	High-Strength Steel Hex Nut Grade 8, 5/16"-18 Thread Size	https://www.mcmaster.com/90499A030/	Round Sample 5 Nuts	10	$0.55	$0.55
Fastener	18-8 Stainless Steel Hex Head Screw 5/16"-18 Thread Size, 2" Long, Fully Threaded	https://www.mcmaster.com/92240A591/	Round Sample 5 High Bolt	1	$0.32	$0.32
Fastener	18-8 Stainless Steel Hex Head Screw 5/16"-18 Thread Size, 1-1/4" Long	https://www.mcmaster.com/92240A585/	Round Sample 5 Low Bolt	1	$0.21	$0.21
Fastener	18-8 Stainless Steel Coupling Nut 5/16"-18 Thread Size	https://www.mcmaster.com/90268A030/	Round Sample 5 Coupling Nut	2	$2.12	$2.12
Fastener	18-8 Stainless Steel Taper Pin Pin Number 3/0, 0.125" Large End Diameter, 1" Long	https://www.mcmaster.com/90681A103/	Crank Pins	1	$8.89	$8.89
Fastener	Plastic Tapered Handle with Revolving Grip 1/4"-20 Threaded Stud, 1-9/16" Long	https://www.mcmaster.com/6308K41/	Crank Grips	2	$13.82	$13.82
Hardware	Self Aligning Linear Ball Bearing Acetal with Steel Ball, for 1/2" Shaft Diameter	https://www.mcmaster.com/8974T1/	Modified Linear Motion Rod Bearings	>3	$29.10	$29.10
Fastener	External Retaining Ring for 7/8" OD, Black-Phosphate 1060-1090 Spring Steel	https://www.mcmaster.com/97633A270/	Modified Linear Motion Rod Snap Rings	8	$2.58	$2.58

	Price/1 Asmbly	Paid/1 Asmbly
Approximate Raw Price	$536.68	$396.11
Approximate Total After Tax and Shipping	**$599.71**	**$438.09**

Notes: "Price/1 Asmbly" reflects the exact cost of purchasing all of the raw materials, hardware, and fasteners necessary for one machine, assuming zero materials are on hand. "Paid/1 Asmbly" reflects the amount spent on all of the raw materials, hardware, and fasteners necessary for one machine, instead taking into account materials on hand or available through university resources.

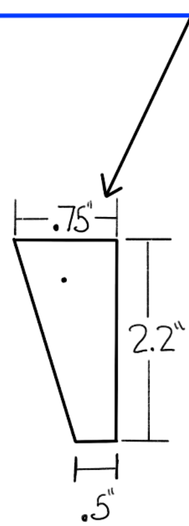
Prices reflect approximate prices at the time of purchase. Prices also reflect the cost for a *single* part necessary for assembly. Oftentimes, retail outlets such as McMaster-Carr only offer parts in packages or longer stock lengths. Thus, the prices reflect the approximate market cost for the bare minimum number of units required for one assembly.

Appendix B: Wedge Grip Concept Layout



The grip faces would likely need to be Diamond serrated pitch 1.5mm, or 1mm

The grip face has dimensions of roughly 1 x 2.2 in



The horseshoe shaped housing moves upward to clamp the specimine. we would need a threaded hole on the housing, while the spinning handle needs to have room for the threaded rod to retract into.

According to the Instron site, the device measurements are:

A=3.4" B=1.9" C=1.9"

Appendix C: Project Budget Information

The following table details the project spending.

Item	Cost
Midwest Metal Supply (two machines worth)	$269.80
AliExpress Load Cell	$50.99
McMaster-Carr Order (main)	$428.97
McMaster-Carr Order (load cell button)	$15.10
HX711 Amazon Load Cell Amplifier	$4.21
McMaster-Carr Supplemental Order	$69.06
McMaster-Carr Supplemental Order (ball bushings)	$106.29
Amazon Tool Order	$57.31
McMaster-Carr Supplemental Order (more ball bushings)	$96.56
Total Spent	$1,098.29

Appendix D: Load Cell Coding

Calibration Code

```
/*
 Calibration Code for Materials Tester MQP (03/02/2022)
 Based off Code Produced by: Nathan Seidle at SparkFun Electronics on November 19th, 2014
 License: Public Domain

 This is the calibration sketch. Use it to determine the calibration_factor that the operational code uses. It also
 outputs the zero_factor useful for projects that have a permanent mass on the scale in between power cycles.

 Setup the load cell in [horizontal/vertical] orientation and start the sketch WITHOUT an applied force on the scale.
 Once readings are displayed, apply a known force to the load cell.
 Press +/- or a/z to adjust the calibration_factor until the output readings match the known force.
 Use this calibration_factor on the operational code.

 This example assumes Newtons (N). To change this, change the Serial.print(" N"); line to the desired unit then
 convert based on calibration factor.

 Your calibration factor may be very different, depending on the orientation of the load cell. If the load cell is in vertical versus horizontal orientation, you must use a separate calibration factor.

 This code uses github user bogde's library: https://github.com/bogde/HX711
 bogde's library is released under a GNU GENERAL PUBLIC LICENSE.

 Arduino pins:
 2 -> HX711 CLK
 3 -> DOUT
 5V -> VCC
 GND -> GND

 Note that most any pin on the Arduino Uno will be compatible with DOUT/CLK.

 The HX711 amplifier can be powered from 2.7V to 5V so the Arduino 5V power works well in this configuration.
```

```
*/

#include "HX711.h"

#define DOUT  3
#define CLK  2

HX711 scale;

float calibration_factor = 0; // +/-830 worked well for a 50N force

void setup() {
  Serial.begin(9600);
  Serial.println("HX711 calibration sketch");
  Serial.println("Remove any loads from load cell");
  Serial.println("After readings begin, apply force to load cell");
  Serial.println("Press + or a to increase calibration factor");
  Serial.println("Press - or z to decrease calibration factor");

  scale.begin(DOUT, CLK);
  scale.set_scale();
  scale.tare(); //Reset the scale to 0

  long zero_factor = scale.read_average(); //Get a baseline reading
  Serial.print("Zero factor: "); //This can be used to remove the need to tare the load cell.
Useful in permanent configurations.
  Serial.println(zero_factor);
}

void loop() {

  scale.set_scale(calibration_factor); //Adjust to this calibration factor

  Serial.print("Reading: ");
  Serial.print(scale.get_units(), 1);
  Serial.print(" N"); //Change this to N and re-adjust the calibration factor if you follow SI
units like a sane person
  Serial.print(" calibration_factor: ");
  Serial.print(calibration_factor);
  Serial.println();

  if(Serial.available())
  {
    char temp = Serial.read();
```

```
    if(temp == '+' || temp == 'a')
      calibration_factor += 5;
    else if(temp == '-' || temp == 'z')
      calibration_factor -= 5;
  }
}
```

Operational Code

```
/*
 Operational Code for Materials Tester MQP (03/02/2022)
 Based off Code Produced by: Nathan Seidle at SparkFun Electronics on November 19th, 2014
 License: Public Domain

 This code operates the load cell and its function with the materials tester.
 See the calibration code to get the calibration_factor for the given
 machine and load cell setup.

 This code uses github user bogde's library: https://github.com/bogde/HX711
 bogde's library is released under a GNU GENERAL PUBLIC LICENSE.

 TO CREATE A STRESS STRAIN CURVE:

  FOR PROPER STRAIN VALUES: set the X value in "Serial.begin(X)" to the number of seconds (converted to milliseconds)
  roughly expended to rotate the machine's crank 1/2 a rotation. This corresponds to a strain of .05 inches or 0.00127 meters.
  This means that roughly, for every reading, assuming the crank is rotating at a relatively constant rate, there is a correct
  corresponding strain value, increasing by 0.00127 m after every reading. The reading numbers will be the 'X' values in graphing.

  FOR PROPER STRESS VALUES: simply take the Y values and divide each value in the set by the cross sectional area of the
  sample in meters squared.

 Arduino pins:
 2 -> HX711 CLK
 3 -> DOUT
 5V -> VCC
```

```
 GND -> GND

 The HX711 amplifier can be powered from 2.7V to 5V so the Arduino 5V power works well in this configuration.

*/

#include "HX711.h"

#define calibration_factor -830.0 // This value is obtained using the calibration code.

#define DOUT  3
#define CLK  2

HX711 scale;

void setup() {
  Serial.begin(9600);
  Serial.println("Materials Tester Force Output");

  scale.begin(DOUT, CLK);
  scale.set_scale(calibration_factor); // This value is obtained using the calibration code.
   scale.tare(); // Assuming there is no force applied to the load cell at start up, reset the scale to 0

  Serial.println("Readings:");
}

void loop() {
  Serial.print("Reading: ");
  Serial.print(scale.get_units(), 1); //scale.get_units() returns a float
  Serial.print(" N"); //
  Serial.println();
}
```